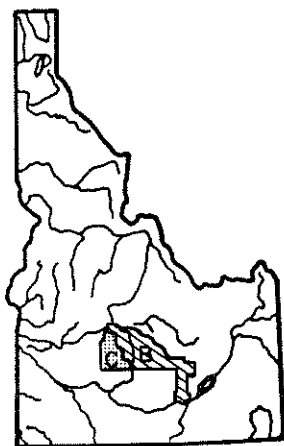


GEOHERMAL INVESTIGATIONS IN IDAHO

PART 7 GEOCHEMISTRY AND GEOLOGIC SETTING OF THE THERMAL WATERS OF THE CAMAS PRAIRIE AREA, BLAINE AND CAMAS COUNTIES, IDAHO



Geothermal water flows into Camas Creek at Magic Reservoir in late fall.

IDAHO DEPARTMENT OF WATER RESOURCES
WATER INFORMATION BULLETIN NO. 30
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GEOHERMAL INVESTIGATIONS IN IDAHO

Part 7

**Geochemistry and Geologic Setting of the
Thermal Waters of the Camas Prairie Area,
Blaine and Camas Counties, Idaho**

by

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**Prepared and published by
Idaho Department of Water Resources
R. Keith Higginson
Director**

September 1976

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PREFACE

Geothermal energy (the natural heat energy of the earth) is receiving nationwide attention. The increasing involvement of many parties in exploration for and development of this energy source has been accelerated by four factors:

1. Ecologically, geothermal energy appears to be a better alternative than other methods of power generation such as nuclear, fossil fuel, or hydroelectric.
2. Economically, it competes favorably with hydroelectric and fossil fuel power generation, and may be cheaper than nuclear methods.
3. Enormous reserves of geothermal resources have been identified and can be developed if the effort is made to utilize them.
4. Efficient use of all energy sources is now recognized as necessary if present energy shortages are to be alleviated and future shortages avoided.

Published information on the geothermal potential in Idaho consists mostly of numerous reports that briefly describe or mention thermal water occurrences in particular areas or regions of the state. Seven reports (Stearns and others, 1937; Waring, 1956; Ross, 1971; Nichols and others, 1972; Warner, 1972; Young and Mitchell, 1973; and Warner, 1975) have been written on Idaho's geothermal potential. Three of the reports are mainly compilations of pre-existing data collected by various investigators over an extended time interval of approximately 50 to 60 years. Waring (1965, p. 26-31) essentially updates the data of Stearns and others (1937, p. 136-151). Godwin and others (1971) classified approximately 15 million acres (60,705 square kilometers) of land in Idaho as being valuable prospectively for geothermal exploration. Ross (1971) published geologic and chemical information on 380 thermal water occurrences, and presented brief evaluations of the geothermal potential of different regions of the state. Nichols and others (1972) identified non-power uses and economic impact of these uses on Idaho. Warner (1972 and 1975) dealt with Idaho's geothermal potential based on its regional geologic setting.

In Idaho, the prospects for early development of geothermal energy as a power source appear excellent. The regional geologic setting appears favorable for the existence of large geothermal fields although little is known of the full potential of this resource. A great deal more must be learned of geothermal occurrence, development, utilization, and regulation. The Idaho Department of Water Resources initiated a study of geothermal potential to generate interest in development of the resource and to properly perform the Department's

regulatory function. Part 1 of the study, prepared jointly with the U.S. Geological Survey, located twenty-five areas in Idaho (fig. 1) where indications of potential for power development utilizing geothermal energy were found. Parts 2, 3, and 4, prepared by the U.S. Geological Survey, studied areas in west-central and southwest Idaho. Parts 5, 6 and 7, prepared by the Idaho Department of Water Resources, studied areas in south-central and southeastern Idaho. Part 8, prepared jointly by the Idaho Department of Water Resources and the Southern Methodist University, describes the heat flow regime in and around the Snake River Plain.

There are four objectives common to each of the studies: (1) to encourage the development of the resource through public knowledge of its occurrence, characteristics, origin, and properties; (2) to develop the expertise within the Department to properly perform its function of regulation of the resource; (3) to protect the ground and surface waters of the state from deleterious effects which might be brought about by large-scale geothermal development efforts by public or private parties; (4) to protect the geothermal resource from waste and mismanagement because of lack of knowledge of its occurrence, characteristics, and properties.

This study, part 7, summarizes a part of the effort to obtain additional data on the properties, origin, occurrence, and characteristics of this resource in Idaho.

ACKNOWLEDGMENTS

Many people have contributed to this study in the hope that the information will be of benefit to the people of the State of Idaho.

The Idaho Nuclear Energy Commission granted financial support for the chemical analyses. Aerojet Nuclear Company, a prime contractor of the Energy Resource and Development Administration, made available laboratory facilities, personnel, and equipment for neutron-activation analyses of thermal water samples at the Idaho National Engineering Laboratory at a very minimal cost. The Bureau of Reclamation made available personnel and laboratory facilities for standard water-quality analyses.

The Department of Chemistry at Idaho State University made available, at no charge, glass-blowing laboratory facilities as part of the neutron activation studies.

Thanks are extended to personnel of the Boise, Idaho and Menlo Park, California offices of the U.S. Geological Survey for their comments and criticisms in review of this manuscript.

All of these cooperative efforts are gratefully acknowledged and appreciated; without such generous support, this study could not have been accomplished.

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ABSTRACT

The thermal waters of the east-west trending intermontane basin making up the Camas Prairie area were sampled during the fall of 1973. Average ground water temperature is 15°C (10°C above mean annual temperature). The thermal waters, chemically similar to thermal waters discharging from granitic rocks elsewhere in Idaho, have high pH, high Na/K and Na/Ca ratios, and high fluoride content. They are low in total dissolved solids (less than 365 mg/l), low in chloride, and exhibit relatively constant chloride/fluoride ratios and silica concentrations.

The widespread occurrence of fluoride-rich thermal waters in Idaho, their close association with granitic rocks, or areas thought to be underlain by such rocks, low concentrations of other volatile constituents, i.e., ammonia and boron, and lack of geyser and fumarolic activity, indicate that the thermal waters of the Camas Prairie area probably lack a magmatic component or are not a separated, condensed steam phase but may be meteoric waters in chemical equilibrium with the Cretaceous granitic rocks underlying and along the margins of the Prairie. The waters move upward into the sediments of the Prairie through faults or fissures with the granites concealed by valley fill material. Some of this water subsequently discharges as thermal springs. The waters could be circulating to depths as shallow as 900 to 1,500 m and cooling by conduction during ascent. Geochemical thermometers are interpreted to indicate that maximum aquifer temperatures in the Camas Prairie Basin are only about 100°C, although higher temperatures were predicted by the quartz equilibrium geochemical thermometer and mixing models.

The Magic Hot Springs well, located near the north shore of the Magic Reservoir at Hot Springs Landing, is an exception to these general conclusions. These waters may be circulating to depths approaching 1,800 to 2,500 m along faults or fissures; or may be due to leakage from an aquifer or reservoir heated by a shallow heat source, related perhaps to the Holocene basalt flows south of Magic Reservoir. These waters are nearly neutral in pH, are much higher in dissolved solids, exhibit higher chloride/fluoride, chloride/carbonate plus bicarbonate, and chloride/sulfate ratios, and are, in general, chemically dissimilar to thermal waters elsewhere in the area.

Temperatures predicted by geochemical thermometers are thought to indicate that Magic Hot Springs well waters are ascending from an aquifer or reservoir with temperatures from 140° to 200°C. Temperatures in this range would be sufficient for application in many industrial processes, including power generation, should sufficient water be available.

GENERAL INTRODUCTION

Purpose and Scope

Reconnaissance geochemical sampling of geothermal waters within Idaho has given indications of at least 25 areas that may have potential for geothermal energy utilization (Young and Mitchell, 1973). The Camas Prairie basin was one of the 25 areas (fig. 1). This region was chosen for further evaluation of its geothermal potential for four reasons:

1. Preliminary geochemical sampling and application of the silica (SiO_2) and sodium-potassium-calcium (Na-K-Ca) geochemical thermometers at several sites indicated the possibility that temperatures might be high enough for power generation at depth in this area.
2. Several thermal springs and wells with easy access meant additional data could be inexpensively and rapidly obtained.
3. Early application of mixing models (Young and Mitchell, 1973, unpublished data) indicated that thermal water temperatures may be much higher at depth than at the surface.
4. Published estimates of geothermal gradient measurements and unpublished heat flow data indicated potential in the area for geothermal power generation.

The purpose of this report is to further examine and evaluate the geothermal potential of the Camas Prairie area by obtaining more thermal-water chemistry data from existing springs and wells; reviewing the literature for pertinent geological, geophysical, and hydrological data; presenting the chemical and physical data; describing the occurrence and chemical characteristics of the thermal waters; interpreting the existing and newly acquired data and relating it to the geothermal potential; developing the information necessary to formulate regulatory strategies if and when deep drilling in the area commences; and recommending areas of additional work where needed.

Well- and Spring-Numbering System

The numbering system used by the Idaho Department of Water Resources and the U.S. Geological Survey in Idaho indicates the location of wells or springs within the official rectangular subdivision of the public lands, with reference to the Boise base line and

meridian. The first two segments of the number designate the township and range. The third segment gives the section number, followed by three letters and a numeral, which indicate the quarter section, the 40-acre tract, the 10-acre tract, and the serial number of the well within the tract, respectively. Quarter sections are lettered a, b, c, and d in counterclockwise order from the northeast quarter of each section (fig. 2). Within the quarter sections, 40-acre and 10-acre tracts are lettered in the same manner. Well 1S-17E-23aab1 is in the NW¼NE¼NE¼ Section 23, T. 1 S., R. 17 E., and was the first well inventoried in that tract. Springs are designated by the letter "S" following the last numeral; for example, 1S-13E-34bcb1S.

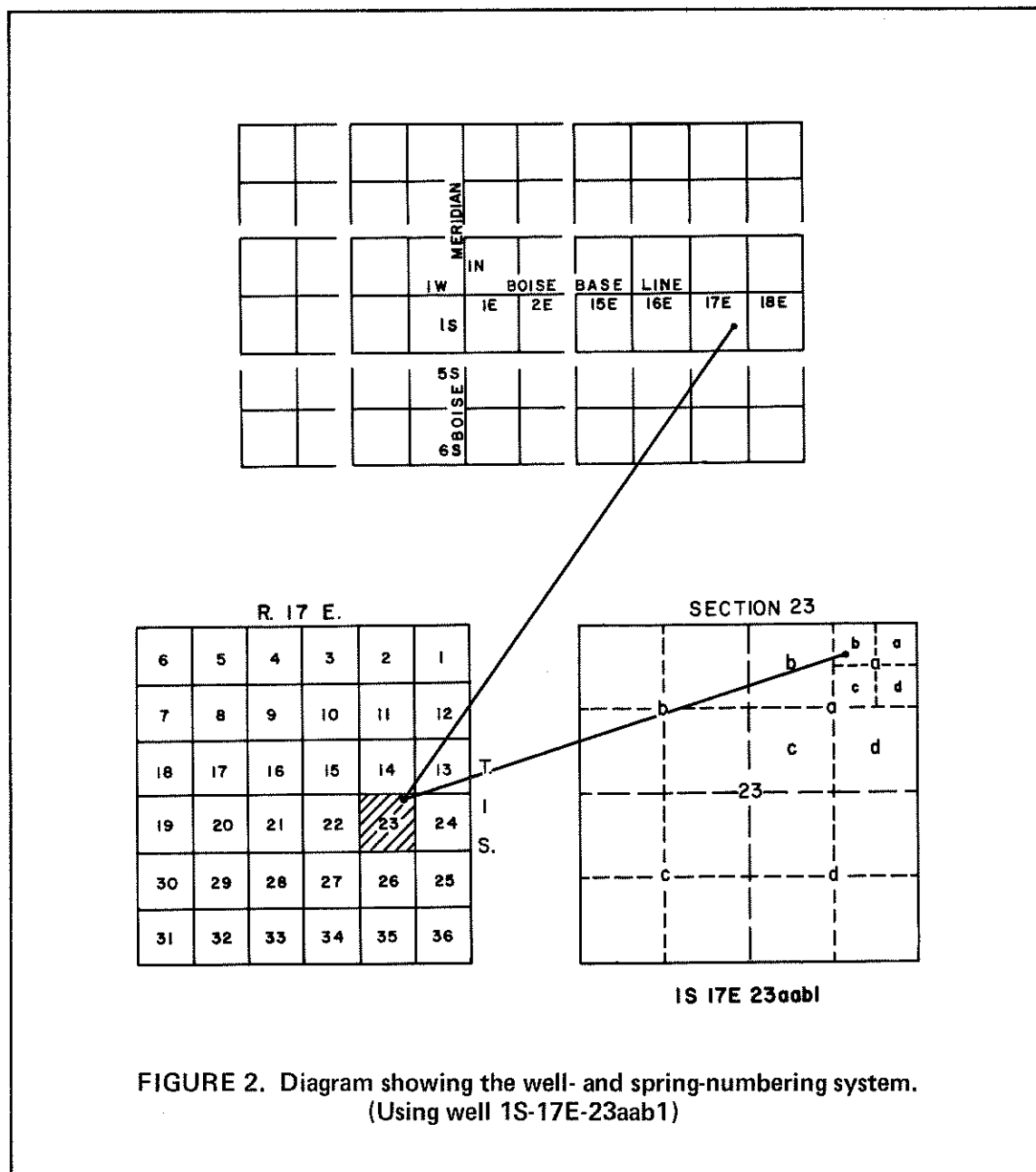


FIGURE 2. Diagram showing the well- and spring-numbering system.
(Using well 1S-17E-23aab1)

Use of Metric Units

The metric or International System (SI) of units is used in this report to present water chemistry data. Concentrations of chemical substances dissolved in the water are given in milligrams per liter (mg/l) rather than in parts per million (ppm) as in some previous Water Information Bulletins. Numerical values for chemical concentrations are essentially equal whether reported in mg/l or ppm for the range of values reported in this report. Water temperatures are given in degrees Celsius ($^{\circ}\text{C}$). Figure 3 shows the relation between degrees Celsius and degrees Fahrenheit.

Linear measurements (inches, feet, yards, miles) are given in their corresponding metric units (millimeters, meters, kilometers). Weight and volume measurements are also given in their corresponding metric units. Table 1 gives conversion factors for these units. Area measurements are listed in both SI and English units except when referring to areas described by official rectangular subdivision of public lands.

TABLE 1
TABLE OF CONVERSION FACTORS

To Convert from	To	Multiply by
inches	centimeters	2.540
feet	meters	0.305
yards	meters	0.914
miles	kilometers	1.609
sq. miles	sq. kilometers	2.589
gallons	liters	3.785
ounces	grams	28.349
centimeters	inches	0.394
meters	feet	3.281
meters	yards	1.094
kilometers	miles	0.621
sq. kilometers	sq. miles	0.386
liters	gallons	0.264
grams	ounces	0.035

Collection of Water Chemistry Data

All known accessible thermal water occurrences in the Camas Prairie area were visited. Several thermal-water samples were collected from each spring system to insure that representative samples were obtained for chemical analysis. Field data collected included measurements of pH, water temperature, and conductivity. The discharge rate from each spring vent or flowing well was measured or estimated. These measurements were made as close as possible to each spring vent or well discharge pipe.

A standard chemical analysis was run on each thermal-water sample taken. Trace metal analyses were conducted using neutron-activation methods. Separate samples were taken for

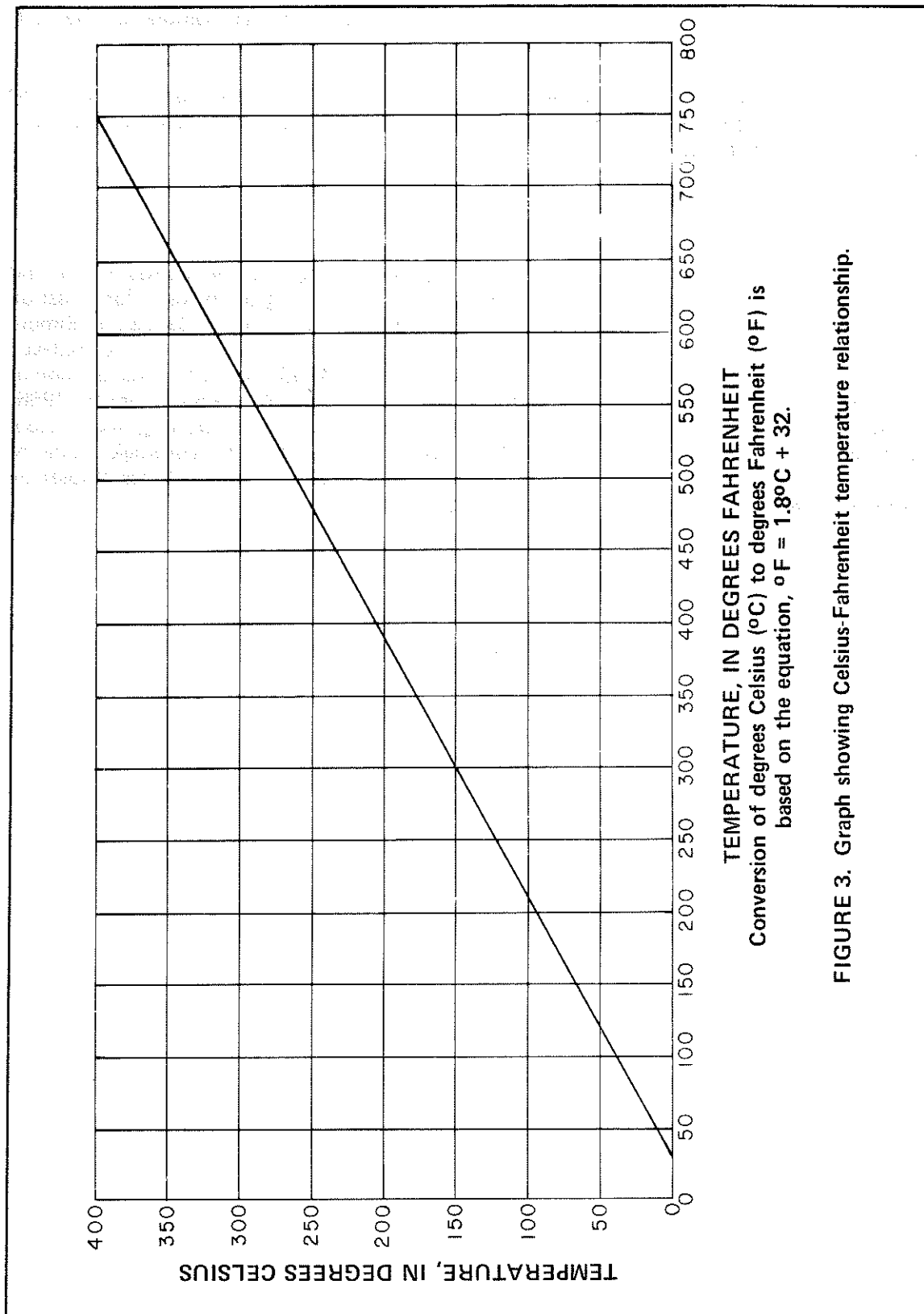


FIGURE 3. Graph showing Celsius-Fahrenheit temperature relationship.

silica analysis and diluted in the field with distilled water (one part sample to nine parts distilled water) to prevent silica polymerization.

Carbonate and bicarbonate determinations were performed potentiometrically in the field because sample holding time was considered to be too short for reliable laboratory analysis of these constituents.

Previous Work

Several reports dealing with the hydrology and geology of the Camas Prairie and adjacent areas are available. Piper (1925) published a report on ground water for irrigation on Camas Prairie. Walton (1962) studied the ground water resources of Camas and Elmore counties. Schmidt and Mackin (1962) studied the Quaternary geology of the Bellevue quadrangle, Camas and Blaine counties. Malde and others (1963) mapped a large portion of southwestern Idaho and included the southern half of the Camas Prairie Basin. Smith (1966) studied the geology of the eastern Mount Bennett Hills in Camas, Gooding, and Lincoln counties, Idaho. Recently, Wallace (1972) compiled a computerized hydrologic model of the Camas Prairie area. Other work is more general in nature and includes studies by Eldridge (1895), Lindgren (1900), and Umpleby (1915).

GEOLOGY

Location and General Features

The Camas Prairie area is located in Camas, Elmore and Blaine counties in south-central Idaho (fig. 1). Walton (1962, p. 8) described the Prairie as an eastward trending intermontane basin. The basin (910 sq. km or 351 sq. miles), some 65 km long and 11 to 16 km wide, lies along the northern boundary of the Snake River Plain and the southern edge of the Idaho batholith. The basin or plain proper is separated from the Snake River Plain by the low-lying, flat-topped Mount Bennett Hills. A low divide flanks the western edge separating the Prairie from the South Fork Boise River drainage basin. To the north, the rugged Soldier Mountains rise abruptly from the Prairie to heights of 3,048 meters (m). On the east, a low divide (Clay Bank Hills) separates the Prairie from the plain of the upper Big Wood River drainage basin.

The relatively flat plain slopes very gently from the west at 1,520 m elevation down to 1,483 m near the Clay Bank Hills. The main drainage to the basin is Camas Creek which meanders sluggishly from west to east where it empties into the Big Wood River via Magic Reservoir. Elk, Corral and Soldier creeks drain the mountain highlands to the north of Camas Prairie and empty into Camas Creek.

Fenneman (1917) placed the Northern Rocky Mountain-Snake River Plain physiographic boundary along the edge of the Mount Bennett Hills. The Prairie, therefore, lies entirely within the Northern Rocky Mountain Physiographic Province.

The main industry is agriculture, principally hay, wheat and cattle. Fairfield, the largest town, has a population of 336 (1970 census).

Walton (1962, p. 5) described the climate of Camas Prairie as being semiarid with low precipitation, high evaporation and large daily fluctuations in temperature. Precipitation in the valley amounts to about 38 centimeters (cm) per year and in the mountain ranges, about 57 cm. The mean annual temperature is about 5°C.

Generalized Geology

Little detailed work pertaining to the geology of Camas Prairie is available. Walton (1962, plate 1) republished Piper's (1925) generalized geologic map of the area. [Malde and others (1963) mapped the Mount Bennett and Clay Bank hills.] These maps were used to compile the geologic map which is included in this report as figure 4.

Igneous rocks ranging in composition from granitic to basaltic and in age from Cretaceous through Pleistocene surround the Camas Prairie basin on all sides. Cretaceous granitic Idaho batholith rocks form a part of the rugged Soldier Mountains on the north and part of the Mount Bennett Hills on the southwest. The Challis volcanic rocks of Eocene(?) to Miocene(?) age consist of rhyolitic to andesitic surface flows which crop out along the north-central portion of the basin where they form part of the Soldier Mountains. The volcanic flows are also found along the southern border areas. Lower Pliocene Idavada volcanic rocks, consisting of silicic latites, are found along the southern margins of the Prairie, while Middle Pleistocene basalt of the Bruneau formation is found on the southeastern and western edges. Holocene basalt flows are found about 6.5 km south of Magic Reservoir between the Big and Little Wood rivers. These flows extend as far south as Shoshone in Lincoln County and as far west as Gooding in Gooding County.

The Prairie area itself consists of alluvium and colluvium of Pliocene to Holocene age. However, it has been mapped as Quaternary alluvium. Wallace (1972, p. 19-21) reported that the sedimentary material was derived mainly from plutonic rocks and rhyolitic and andesitic lava flows from the northern mountains. These sediments accumulated in the Camas Prairie basin mostly during Pliocene-Pleistocene time while Camas Creek was cutting through lava barriers which had dammed the outlet to the east. The characteristics of these deposits change markedly from place to place due to complex deposition conditions. The sediments are, in general, poorly sorted, with sizes ranging from clay to boulders. They contain numerous lenses and interfingering clay and silt deposits, as well as sands and gravels. Walton (1962, p. 15) reported that two distinct fresh water artesian aquifers (an upper and lower) exist in the valley fill sediments. These artesian aquifers average 15 and 25 m in thickness and 75 and 150 m in depth below land surface, respectively. Both are composed of fine grained sands and gravels of low permeability. Wallace (1972, p. 60) on the basis of chemical analyses of water from these aquifers and the shallow, unconfined water table aquifer determined that Camas Prairie contained essentially a single flow system. Wallace (1972, p. 60), however, felt it possible that the thermal water which is found in the valley (see fig. 4 for locations) is added to the Camas Prairie system through deep circulation of water from the granitic and volcanic rocks surrounding the area. Walton (1962, p. 13) reported that the entire thickness of the valley fill had been penetrated by two irrigation wells in which bedrock was found at depths of 151.5 and 167.4 m below land surface. These wells are located near the center of the valley, both "bottomed" in Cretaceous granitic rock. Walton's geologic cross sections are shown in figures 5 and 6.

Structural Features

The structural framework of the Camas Prairie basin is to a large extent unknown. Some structural features in the southern border areas have been mapped (fig. 4). Cretaceous granitic rocks of the Idaho batholith on both the northern and southern borders and at shallow depth near the center of the valley suggest that the basin is nothing more than a shallow depression in the granite surface that has been partially filled with sediments derived from the marginal highlands.

Smith (1966, p. 98), however, referred to the Camas Prairie basin as a graben and found evidence for fault control for the Prairie basin in his study of the Mount Bennett Hills. This east-west trending range is a complexly faulted, southerly and easterly tilted horst (upthrown fault block). This range, consisting of Cretaceous to Miocene age rocks, plunges eastward beneath Pliocene and Pleistocene volcanic and sedimentary rocks. Smith mapped

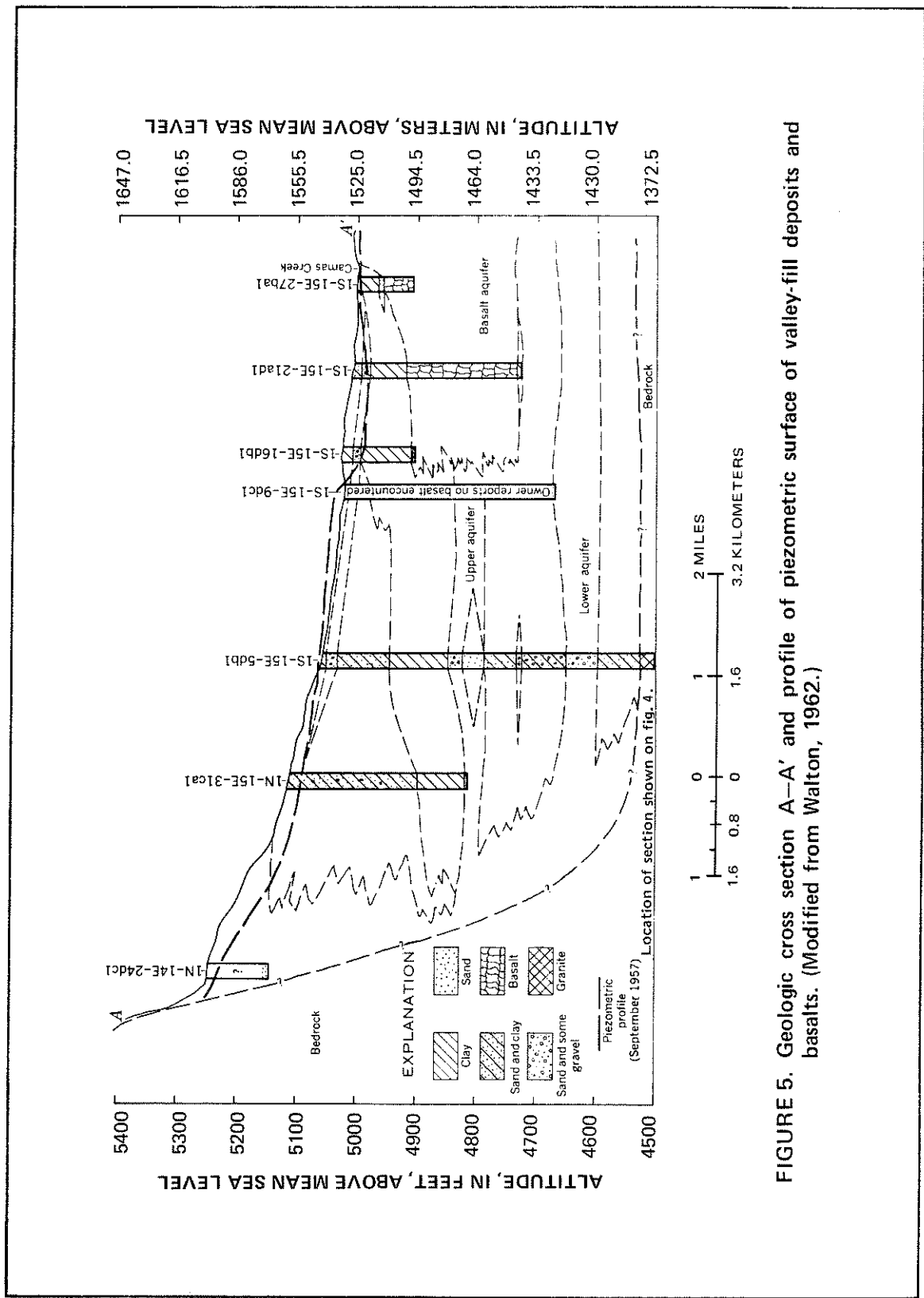


FIGURE 5. Geologic cross section A-A' and profile of piezometric surface of valley-fill deposits and basalts. (Modified from Walton, 1962.)

ALTITUDE, IN FEET, ABOVE MEAN SEA LEVEL

5400
5300
5200
5100
5000
4900
4800
4700
4600
4500

1647.0
1616.5
1586.0
1555.5
1525.0
1494.5
1464.0
1433.5
1430.0
1372.5

Bedrock

Camas Creek

1N-14E-33bb1

1S-14E-9db1

1S-14E-9da2 (Village of Fairfield)

1S-14E-22db1

1S-14E-27ad1

2S-14E-11da1

Upper aquifer

Lower aquifer

Bedrock

EXPLANATION

- Clay
- Sand and some gravel
- Gravel
- Sand and clay
- Granite
- Piezometric profile
- Sand

1 0 1 2 MILES

1.6 0 1.6 3.2 KILOMETERS

Location of section shown on fig. 4.

(September 1957)

many normal faults which he classed into two roughly conjugate sets. The northwest trending set has a distinct en echelon relationship to the Mount Bennett Hills. This set, of probably early Pleistocene age with largely dip-slip, down to the north, nearly vertical movements, has a cumulative displacement in excess of 300 m (Smith 1966, p. 108).

Landsat false color infrared satellite imagery reveals several curvilinear features near Magic Reservoir. These features could represent the surface expressions of major faults in this area.

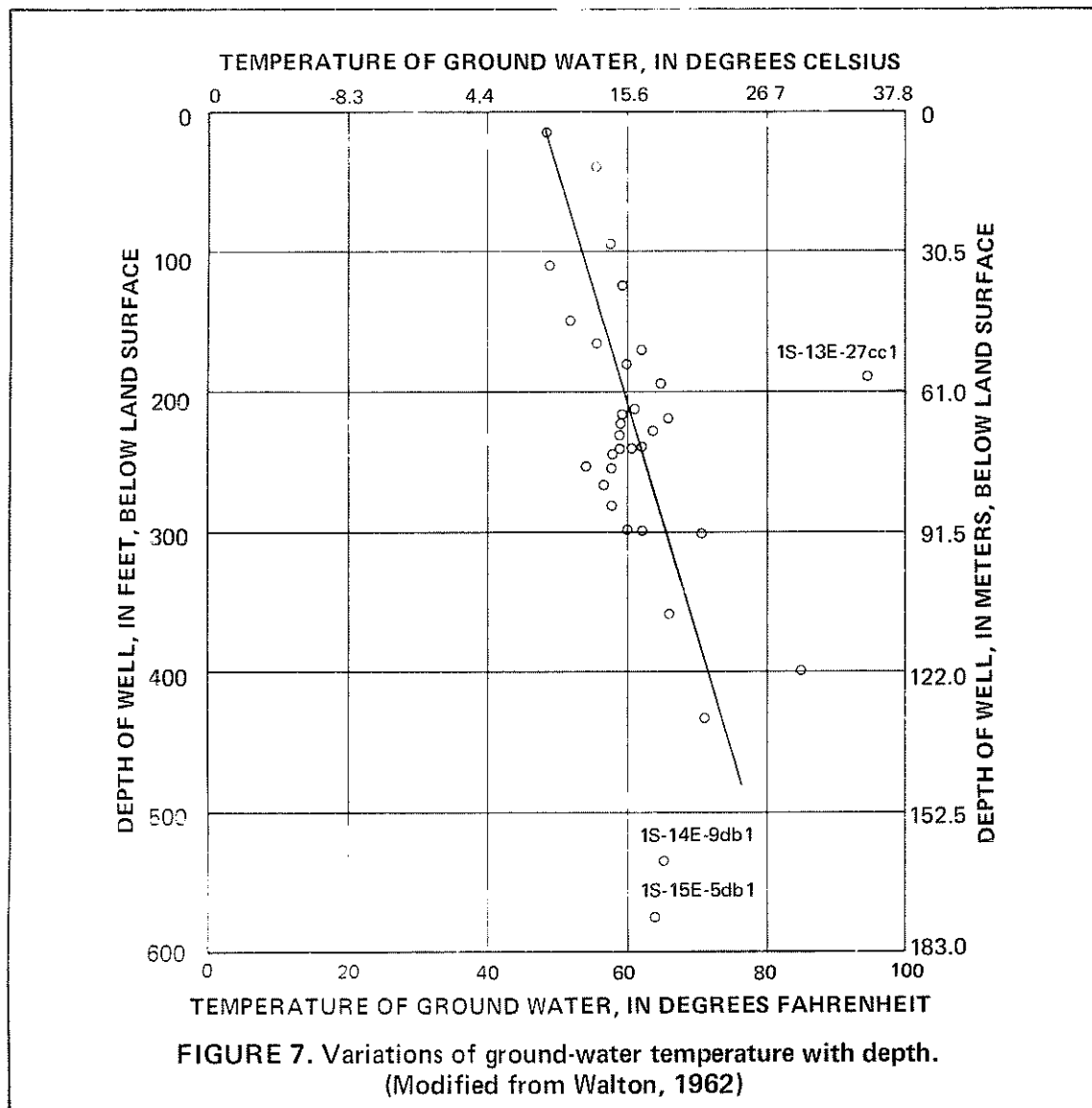
Geothermal Gradient and Heat Flow

Although not extremely reliable as predictors of drilling depths, geothermal-gradient measurements have been used in geothermal investigations to establish boundary conditions or possible limits to which one might reasonably expect water to be circulating. A temperature-versus-depth plot (fig. 7) for cold-water wells in the Camas Prairie area was made by Walton (1962, p. 40), who obtained a geothermal gradient of 92°C per km from this plot. This gradient has been confirmed by actual gradient measurements in water wells in the Camas Prairie area by Brott and others (1976). This gradient is much higher than the normal geothermal gradient of 33°C per km. An average geothermal gradient of this magnitude extending uniformly to great depths suggests that a temperature of 200°C would exist at a depth of approximately 2,000 m. For a temperature of 85°C (approximately that observed at the surface for the hottest thermal water known in the Camas Prairie area) water would have to circulate to depths of less than 900 m. This geothermal gradient may decrease within the granitic rocks underlying the Prairie by approximately one-half due to thermal conductivity changes. Consequently, actual circulation depths to reach temperatures of 85 and 200°C may be proportionately greater.

The greater reliability of heat-flow measurements over simple temperature-gradient measurements or calculations in assessing an area's geothermal potential is well known. The geothermal gradient may be viewed as the potential difference between the earth's deeper layers and that found at the surface, and is dependent on the ability of the intervening rock layers to conduct heat (thermal conductivity). Heat flow measurements take this thermal conductivity into account and, therefore, are uniform with depth, while abrupt and sometimes large variations in geothermal gradient occur with depth due to changes in thermal conductivity. A high heat flow, therefore, may indicate the presence of an intense heat source (regional or local) in the subsurface, while a high geothermal gradient may only reflect a lower thermal conductivity.

Although the thermal conductivity of the intervening rock layers in the Camas Prairie area is not exactly known, reasonable heat flow assumptions can be made by simply knowing the limits of thermal conductivity of the types of rocks found in the area. For example, unconsolidated, poorly sorted sands and gravels usually exhibit a thermal conductivity in thermal conductivity units (TCU) between 2.0 and 5.0 millicalories per centimeter per sec per $^{\circ}\text{C}$ - millical/cm/ $^{\circ}\text{C}$ sec giving a heat flow, in heat flow units (HFU), of from $92^{\circ}\text{C}/\text{km} \times 2.0 \text{ TCU} = 1.8$ microcalories per sq cm per sec ($\mu\text{cal}/\text{cm}^2\text{sec}$) (1.8 HFU) as a lower limit and $92^{\circ}\text{C}/\text{km} \times 5 \text{ TCU} = 4.5$ HFU as an upper limit. A heat flow of 3 HFU would be twice that which is considered normal (1.5 HFU) for most of the United States, but which appears to be typical of the margins of the Snake River Plain region (Brott and others, 1976).

This above normal heat flow appears typical of granitic terrains making up much of the complex Idaho batholith (Blackwell, 1973 unpublished data) and is high enough to



reasonably expect that the thermal waters in the area could be reaching maximum temperature through deep circulation. The heat flow in the Camas Prairie area might be related to the Cretaceous granitic rocks of the Idaho batholith which are known to underlie the valley fill sediments in parts of the Prairie. The cause of this high heat flow is not known. Speculations are a crustal heat source or a mantle heat source due to crustal thinning.

Geothermal gradient measurements and heat flow calculations have not been made in the eastern portion of the Prairie area due to a lack of suitable bore holes. However, high heat flow in this part of the study area is indicated by its marginal position relative to the Snake River Plain and thermal water discharges near Magic Reservoir. A buried stock or sill, related perhaps to the Holocene basalt flows south of Magic Reservoir could conceivably underlie the area acting as a local, high intensity heat source.

THERMAL SPRINGS AND WELLS AND THEIR GEOCHEMISTRY

Location and General Description

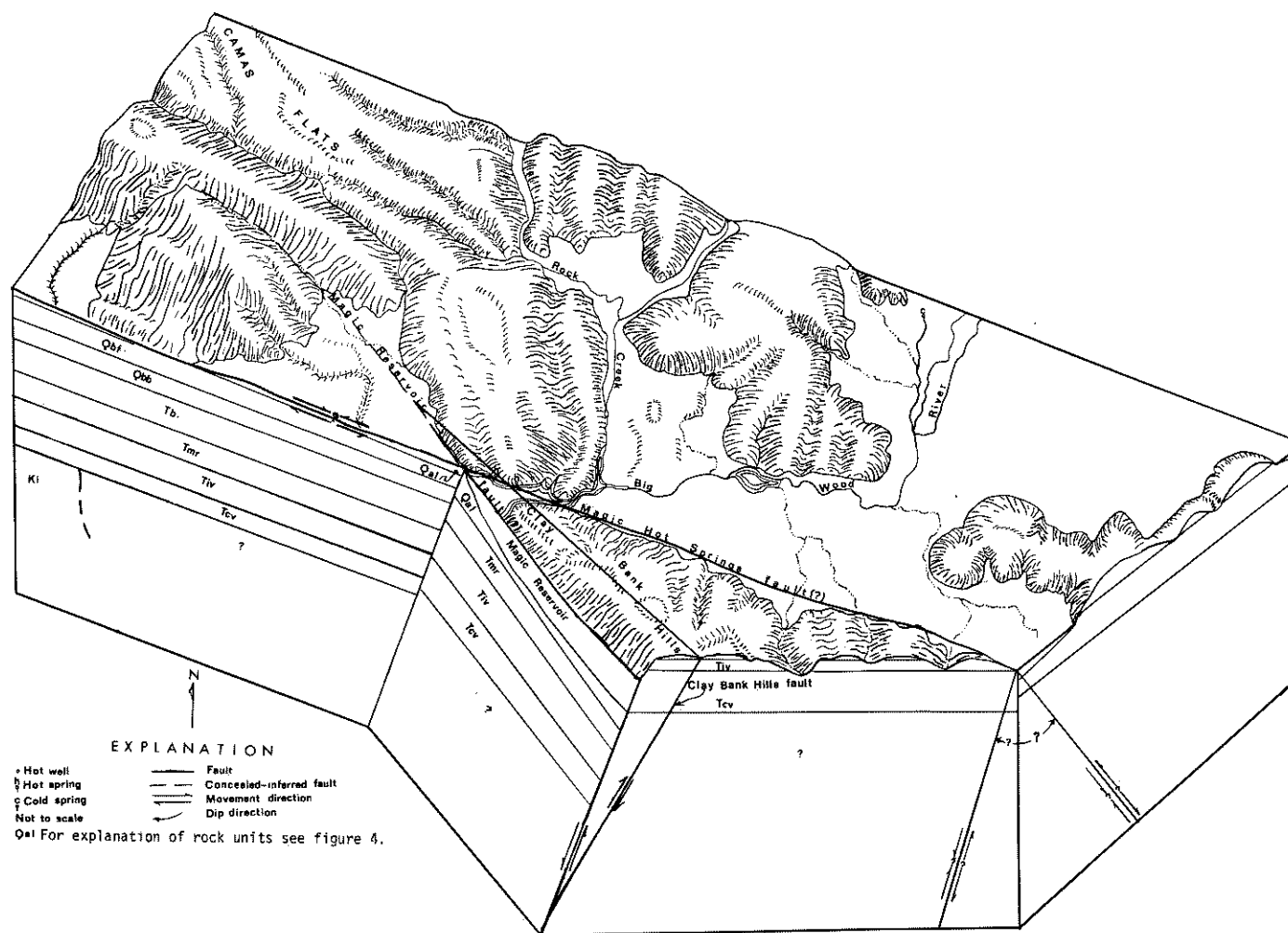
Thermal water occurrences in the Camas Prairie area are not limited to any one locality or rock type but are found sparsely distributed over a large area (fig. 4). The occurrences seem more abundant, however, in the western reaches where Hot Springs Ranch (1N-13E-32abc1-3S), Barron's Hot Springs (1S-13E-34bcb1-3S), Spring No. 1S-12E-16cba1S-cab1S, and several warm artesian wells are located. These springs issue from alluvial valley fill deposits. The wells were drilled into valley fill alluvium.

Elk Creek Hot Springs (1N-15E-14ada1-3S) are located in the eastern part of the study area and issue from fractures in Cretaceous granitic rocks near Eocene(?) to Miocene(?) Challis volcanic rocks.

Magic Hot Springs well (1S-17E-23aab1) is located in the extreme eastern part of the study area on the northern shore of Magic Reservoir. This well was drilled near the intersection of two curvilinear features that are probably faults. These faults may represent the controlling structure for the occurrence of thermal water in this particular part of the study area. Landsat false color infrared satellite imagery shows one of these lineaments as extending northwesterly, from near the southern tip of Magic Reservoir, along its eastern shoreline, and into the Soldier Mountain at the northern margin of the study area. The other feature extends at a slight northwesterly angle along the northern margin of the Claybank Hills and into the Soldier Mountains. [Malde and others (1963) show a fault lying somewhat east of and nearly parallel to the Magic Reservoir(?) fault. Their mapped fault passes through the Clay Bank Hills and lies very near Magic Hot Springs well.] A hypothetical block diagram showing the possible control of Magic Hot Springs well is shown in figure 8.

Several other thermal waters (notably warm artesian wells) were not flowing at the time they were visited and samples could not be collected for analysis. Thermal water deposits were absent at all visited springs and wells except for very minor evaporative incrustations around discharge pipes of some of the wells. Discharges of the various sampled springs and most wells are also low. Measured surface temperatures range from 26° to 72°C and averaged 53°C. In general, ground waters in this area are about 10°C above mean annual temperature.

FIGURE 8. Idealized block diagram of the Magic Reservoir Area in Camas and Blaine counties depicting theoretical structural control for Magic Hot Springs well. In reality, the faults depicted may represent more broadly defined zones of faulting rather than single plane surfaces as represented on paper. The trend of these features are fairly well known, but the direction of movement of the Magic Hot Springs fault is unknown.



Geochemical Data

Major Constituents

Standard water quality chemical data from known thermal water occurrences in the Camas Prairie area are given in table 2. These analyses provide a chemical comparison of thermal waters in the area and were used to calculate selected chemical-constituent ratios and to estimate aquifer temperatures.

In general, the thermal waters of the Camas Prairie area can be classified as sodium bicarbonate (NaHCO_3) type waters although the dominant element found in Hot Springs Ranch (1N-13E-32abc1-3S) water is silica rather than sodium. With the exception of Magic Hot Springs well (1S-17E-23aab1) these thermal waters are typified by:

1. High silica contents (50-90 mg/l) compared to low total dissolved solids of less than 365 mg/l;
2. High pH (7.8-9.2);
3. High carbonate compared to most thermal water in Idaho;
4. High fluoride contents compared to most thermal and cold ground waters in Idaho;
5. Low calcium (Ca) magnesium (Mg), potassium (K), and chloride (Cl) contents.

Typically, these thermal waters are chemically similar to thermal waters found discharging from Cretaceous granitic rocks, or areas believed to be underlain by these type rocks elsewhere in Idaho (Ross, 1971, p. 23), (Young and Mitchell, 1972, unpublished data, and Young and Whitehead, 1975a, p. 30).

The cause of this chemical "fingerprint" for these waters is not well understood. At least three hypotheses might explain some of the observations.

1. Abundance of certain elements may reflect the availability of the elements in various minerals found in the granitic rocks and the minerals' solubility in heated water or steam. For example, the high fluoride content might be traced to the abundance of some fluorite-rich mineral such as fluorite or fluorapatite and its solubility at reservoir temperature and pH, or to fluoride, concealed in interlattice silicate structures of hydroxyl bearing minerals such as the micas or amphiboles, which are found in the granitic rocks.
2. High fluoride waters may reflect an appreciable quantity of magmatic waters or volcanic gasses. Observations of gasses from volcanoes indicate magmatic waters should generally be high in volatiles such as fluoride, ammonia and boron.
3. High fluoride waters might be explained by enrichment of fluoride in a steam phase separated from water having a lower fluoride content (volatile enrichment).

TABLE 2
CHEMICAL ANALYSES OF THERMAL WATERS FROM THE CAMAS PRAIRIE AREA,
CAMAS AND BLAINE COUNTIES, IDAHO
(Chemical constituents in milligrams per liter)

Spring or well identification number and name	Measured surface temperature (°C)	Reported well depth below land surface (meters)	Discharge (l min.)	Silica (SiO ₂)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Phosphate (PO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)	Boron (B)	Ammonia (NH ₃)	Specific conductance (field)	pH (field)	Dissolved solids (calculated) (TDS)	Sodium adsorption ratio (SAR)
Hot Springs Ranch 1N-13E-32abc1S	60		-	81	1.0	0	56	0.8	45	36	11	0	5.7	3.7	0.03	0	0	226	9.2	118	15.4
Hot Springs Ranch 1N-13E-32abc2S	67		95	78	1.0	0	56	2.0	58	30	12	0	5.7	3.3	.70	0	0	215	9.2	132	15.4
Hot Spring Ranch 1N-13E-32abc3S	64		-	78	1.2	0.10	55	1.2	54	32	11	0	5.7	3.2	.09	0	0	220	9.2	127	12.8
Elk Creek Hot Springs 1N-15E-14ada1S	55		95	82	2.2	.10	91	2.0	65	2.4	44	0	23	18	.10	0.01	0	333	8.9	225	16.2
Elk Creek Hot Springs 1N-15E-14ada2S	55		8	83	2.4	.10	92	1.6	96	1.2	44	0	23	16	.10	.01	0.10	376	8.9	257	15.7
Elk Creek Hot Springs 1N-15E-14ada3S	45		8	78	2.2	0	92	1.6	96	2.4	48	0.01	24	17	.86	.01	0	418	8.9	262	17.1
1S-12E-16cba1S	45		-	68	0.8	0	49	0.4	4.9	51	8.2	0	3.2	1.9	.06	0	0	206	9.9	66	15.1
1S-12E-16cab1S	49		-	68	1.0	0	49	0.8	0	57	7.7	0	4.2	2.0	.04	0	0	208	9.9	61	13.5
1S-13E-22ccc1	26	57.7	5	78	3.0	.60	86	2.4	193	0	5.3	.03	10	9.8	.00	.02	1.3	460	7.8	297	11.8
1S-13E-27ccb1	35	57.7	-	83	3.0	.10	94	1.6	21	0	5.8	.02	11	11	.02	.02	.50	491	8.0	134	14.5
1S-13E-27ccb2	45	117	-	64	2.2	.10	99	2.0	215	0	9.1	.03	12	10	.02	0	.10	411	8.5	337	17.6
Barron's Hot Springs 1S-13E-34bcc1	49		-	84	3.4	.10	106	2.7	211	0	12	0	14	13	.19	.02	0	347	8.3	346	15.4
Barron's Hot Springs 1S-13E-34bcc1S	73		40	84	3.6	.10	108	3.1	227	0	13	.01	13	13	.00	.02	.10	335	8.2	364	15.3
Magic Hot Springs Well 1S-17E-23aab1	72	79.0	20	105	20	.10	321	23	735	0	52	.01	85	10	.56	.08	.10	1,149	6.9	1,213	19.6

Analyses by: U.S. Bureau of Reclamation

The first explanation of the high fluoride content is considered by this author to be the best hypothesis because of:

1. The widespread occurrence of fluoride-rich thermal waters in Idaho;
2. Their close association with granitic rocks or areas believed to be underlain by granitic rocks;
3. Lack of fumarolic, geyser, and related geothermal activity (which would indicate volatile enrichment processes are actively taking place);
4. Low concentrations of other volatiles, i.e., ammonia and boron, chemical constituents found in volcanic gasses, and which are also capable of enrichment in separated steam. In nearly all geothermal systems investigated to date, isotopic studies have not revealed any magmatic or juvenile water contributions to these systems.
5. Thermodynamic calculations indicate that thermal waters from Elk Creek Hot Springs (1N-15E-14ada1-4S), which issue directly from fractures in granitic rocks, are in equilibrium with fluorite at the measured spring temperatures. Fluorite is known as an accessory mineral in certain granitic rocks in Idaho.
6. In general, granitic rocks are known to contain relatively much fluoride, mostly in fluorapatite, but, in some cases, as fluoride concealed in interlattice spaces of hydroxyl bearing minerals such as the micas or amphiboles where it substitutes for hydroxide due to size and charge similarities.

Trace Metals

Trace metal analyses performed by neutron-activation techniques are listed in table 3. These give an insight into the likelihood of mineral extraction from thermal waters in the area. Valuable metals are known to be associated with geothermal brines in certain parts of the world. Knowledge of trace metal constituents are also valuable in engineering design for hot water extraction and utilization methods. Certain elements may represent potential pollution hazards if present in sufficient quantities.

Extremely low concentrations of nearly all analyzed trace elements were, however, detected in these thermal waters. Iron, strontium, and barium were trace metals which occurred in highest concentrations found in any of the waters of the Camas Prairie area. The highest concentrations of these three elements were found in Magic Hot Springs well water. Chromium, cobalt, and silver were undetected in water from this well. All elemental concentrations are in the micrograms per milliliter range.

Geochemical Thermometers and Atomic Ratios

Preliminary evaluations of geothermal systems are being successfully conducted using geochemical thermometers. In the Raft River Valley of southeastern Idaho, the reliability of these thermometers has been tested by deep drilling. The silica and Na-K-Ca predicted aquifer temperatures (Young and Mitchell, 1973) and mixing model calculations (Young

TABLE 3
TRACE METAL ANALYSES OF THERMAL WATERS
FROM THE CAMAS PRAIRIE AREA
CAMAS AND BLAINE COUNTIES, IDAHO
(Chemical constituents in milligrams per liter)

Spring or well identification number & name	Scandium Sc	Chromium Cr	Iron Fe	Cobalt Co	Zinc Zc	Rubidium Rb	Strontium Sr	Silver Ag	Antimony Sb	Barium Ba	Cesium Cs
	$\times 10^{-8}$	$\times 10^{-6}$	$\times 10^{-4}$	$\times 10^{-7}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-4}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-5}$	$\times 10^{-7}$
Hot Springs Ranch 1N-13E-32abc1S	0.32	0.59	0.18	0.22	0.30	0.28	0.24	0.06	-	.98	1.0
Elk Creek Hot Springs 1N-15E-14ada1S	1.5	1.3	1.6	.69	2.2	.61	.92	-	-	3.0	1.4
1S-12E-16cab1S	.34	1.4	.25	.43	.47	.25	.18	.13	0.22	3.2	.57
1S-13E-22ccc1	.43	2.1	1.6	1.0	.89	.21	.26	.37	.41	13	.05
1S-13E-27ccb2	.28	1.5	.34	.54	.61	.50	.23	.27	1.0	3.2	2.9
Barron's Hot Springs 1S-13E-34bcb1S	1.5	.44	.39	9.0	.76	1.4	.81	-	.83	7.6	7.8
Magic Hot Springs Wells 1S-17E-23aab1	.45	-	2.3	-	.18	11	7.7	-	1.5	11	40
- Not detected.											
Analyses by: Idaho National Engineering Laboratory.											

and Mitchell, 1973, unpublished data) agreed very closely (within 10°C) with temperatures found at depth (Kunze, 1975). This proven reliability in the Raft River Valley gives some measure of confidence in applying the same methods to other similar areas of the state.

The degree of reliance to be placed on a geochemical thermometer depends on many factors. A detailed description of the basic assumptions, cautions, and limitations for these geochemical thermometers is included in the Appendix. The basic assumption is that the chemical character of the water obtained by temperature dependent equilibrium reactions in the thermal aquifer is conserved from the time the water leaves the aquifer until it reaches the surface. The concentration of certain chemical constituents dissolved in the thermal water can, therefore, be used to estimate aquifer temperatures.

Aquifer temperatures calculated from the silica, Na-K-Ca geochemical thermometers, and mixing models, as well as the atomic ratios of selected elements found in the thermal waters of the Camas Prairie area are given in table 4. These were calculated from values of concentration found in table 2.

TABLE 4

**ESTIMATED AQUIFER TEMPERATURES AND ATOMIC RATIOS
OF SELECTED CHEMICAL CONSTITUENTS**

Spring or well identification number and name	Discharge (l min.)	Measured surface temperature (°C)	Aquifer temperatures from geochemical thermometers rounded to 5°C (see footnotes)								Atomic Ratios													
			T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	%	Sodium Potassium	Sodium Calcium	Magnesium Calcium	Ca/HCO ₃	Chloride Carbonate *	Chloride Bicarbonate	Cl/F	Cl/B	Ammonia Chloride	Ammonia Fluoride	√Ca/Na	Chloride Sulfide	Ca/F
												Na/K	Na/Ca	Mg/Ca	Ca/HCO ₃	Cl/CO ₂ +HCO ₃	Cl/F	Cl/B	NH ₄ /Cl	NH ₄ /F	√Ca/Na	Cl/CO ₄	Ca/F	
Hot Springs Ranch 1N-13E-32abc1S	-	60	125	125	5	100	75	30	185	140	73	122	97.6	-	0.03	0.12	0.83	434	-	-	-	2.05	1.40	0.128
Hot Springs Ranch 1N-13E-32abc2S	95	67	125	120	5	95	135	90	170	135	66	47.6	97.6	-	.03	.11	.93	-	-	-	-	2.05	1.29	0.144
Hot Springs Ranch 1N-13E-32abc3S	-	64	125	120	5	95	85	55	170	135	69	77.9	79.9	0.16	.03	.11	.95	-	-	-	-	2.29	1.40	0.178
Elk Creek Hot Springs 1N-15E-14ada1S	95	55	125	125	5	100	95	55	195	145	78	77.3	72.1	.09	.05	.59	.68	700	-	-	-	1.87	1.42	0.068
Elk Creek Hot Springs 1N-15E-14ada2S	8	55	125	125	5	100	85	40	200	145	78	97.7	66.8	.08	.04	.41	.77	500	0.01	0.01	1.93	1.42	0.071	
Elk Creek Hot Springs 1N-15E-14ada3S	8	45	125	120	5	95	85	40	220	150	85	97.7	72.9	-	.03	.42	.76	522	-	-	-	1.85	1.35	0.061
IS-12E-16cab1S	-	45	115	115	-	90	55	5	190	140	83	213	106.7	-	.25	0	.90	243	-	-	-	2.10	1.06	0.200
IS-12E-16cab1S	-	49	115	115	-	90	75	35	180	140	79	106	85.4	-	0	.12	1.13	639	-	-	-	2.34	1.48	0.237
IS-13E-22ccc1	5	26	125	120	5	95	90	70	999	200	89	60.9	49.9	.34	.02	.09	.55	190	.27	.15	2.31	5.11	0.145	
IS-13E-27ccb1	300	35	125	125	5	100	80	40	999	175	61	99.9	54.6	.07	.22	.90	.54	197	.09	.05	2.12	5.14	0.129	
IS-13E-27ccb2	-	45	115	110	-	100	95	50	180	140	81	84.1	78.4	.09	.02	.10	.64	-	.01	.01	1.72	3.57	0.104	
Barron's Hot Springs IS-13E-34bcc1	-	49	125	125	10	85	95	65	220	150	83	66.7	54.3	.06	.02	.11	.58	236	-	-	-	2.00	3.16	0.124
Barron's Hot Springs IS-13E-34ccb1S	40	73	125	125	10	100	125	75	170	135	62	59.2	52.3	.05	.02	.10	.54	198	.01	.01	2.02	2.71	0.131	
Magie Hot Springs Well IS-17E-23aab1	20	72	140	135	20	115	175	150	200	145	69	23.7	27.9	.01	.04	.20	4.56	323	-	.01	1.60	4.43	0.945	

T₁ = Silica temperatures assuming quartz equilibrium and conductive cooling (no steam loss).
T₂ = Silica temperatures assuming quartz equilibrium and adiabatic expansion at constant enthalpy (maximum steam loss).
T₃ = Silica temperatures assuming quartz equilibrium with amorphous silica.
T₄ = Silica calculated aquifer temperatures assuming equilibrium with chalcedony.
T₅ = Na-K temperatures.
T₆ = Na-K temperatures.
T₇ = Na-K temperatures.
T₈ = Na-K temperatures.
% = Percent of cold water in T₇ calculation.
+ = Molar ratio.
- = Data not possible to obtain.
999 = Hot temperature calculation not possible.

Discussion of Geochemical Data

The geochemical data suggest that the thermal waters in the Camas Prairie area are from low temperature systems. The chalcedony equilibrium geochemical thermometers (T_4 , table 4) or Na-K-Ca geochemical thermometer (T_5 , table 4) are considered the most reliable and representative of actual aquifer temperatures in most cases because of these considerations:

1. Thermal waters issuing from granitic terrains are generally considered to be supersaturated with silica with respect to quartz (Holland 1967, p. 393). Therefore, the quartz equilibrium geochemical thermometer (T_1 & T_2) and mixing models (T_7 & T_8) may not be valid because of excess silica in many of the these springs and wells.
2. In no case does amorphous silica control silica concentration in the thermal water. The below-measured surface temperatures and in some cases below-zero temperatures predicted by the amorphous silica thermometer indicate that the thermal waters are considerably undersaturated with silica with respect to this phase. No exceptions to this generalization were noted from table 4.
3. No unusual conditions suggestive of mixed hot and cold waters, such as cold spring seeps in the vicinity of the hot springs or wells, were observed.
4. Discharges were, in general, very low throughout the area, indicating little, if any, mixing of hot and cold waters. Exceptions to the low discharges are found only in drilled holes.
5. The low Na-K-Ca predicted aquifer temperatures are in general agreement with measured surface temperatures, indicating little mixing of hot and cold water, or that equilibrium conditions have been maintained since the waters have left the thermal aquifer. The low predicted Na-Ka-Ca aquifer temperatures show fair agreement with the chalcedony equilibrium aquifer temperatures.
6. The low chloride and certain other element concentrations found in these thermal waters could be the result of mixing. However, mixing would dilute certain other chemical constituents found in relatively high concentrations such as fluoride and carbonate.
7. Walton (1962, table 2, p. 35) reported higher calcium concentrations in cold ground waters in the area than were found in the thermal waters. Dilution of thermal waters with cold ground waters would mean the premixed thermal waters would have to be nearly devoid of calcium in order for the mixed water to show the calcium concentration found in the thermal waters. Thermal water devoid of calcium from granitic rocks is considered unlikely.
8. The extremely widespread geographical area in which these type waters are found would make it highly unlikely that such uniform mixing conditions could exist as to recognize these waters by merely looking at unsynthesized geochemical data.
9. Arnórsson (1970, p. 537, 1975, p. 763) found that chalcedony generally controls silica concentration in Icelandic thermal waters when aquifer temperatures are

below 100-110°C Chalcedony equilibrium aquifer temperatures are below Arnórsson's upper limit. Chalcedony equilibrium is, therefore, indicated if this criterion is applicable to the Camas Prairie.

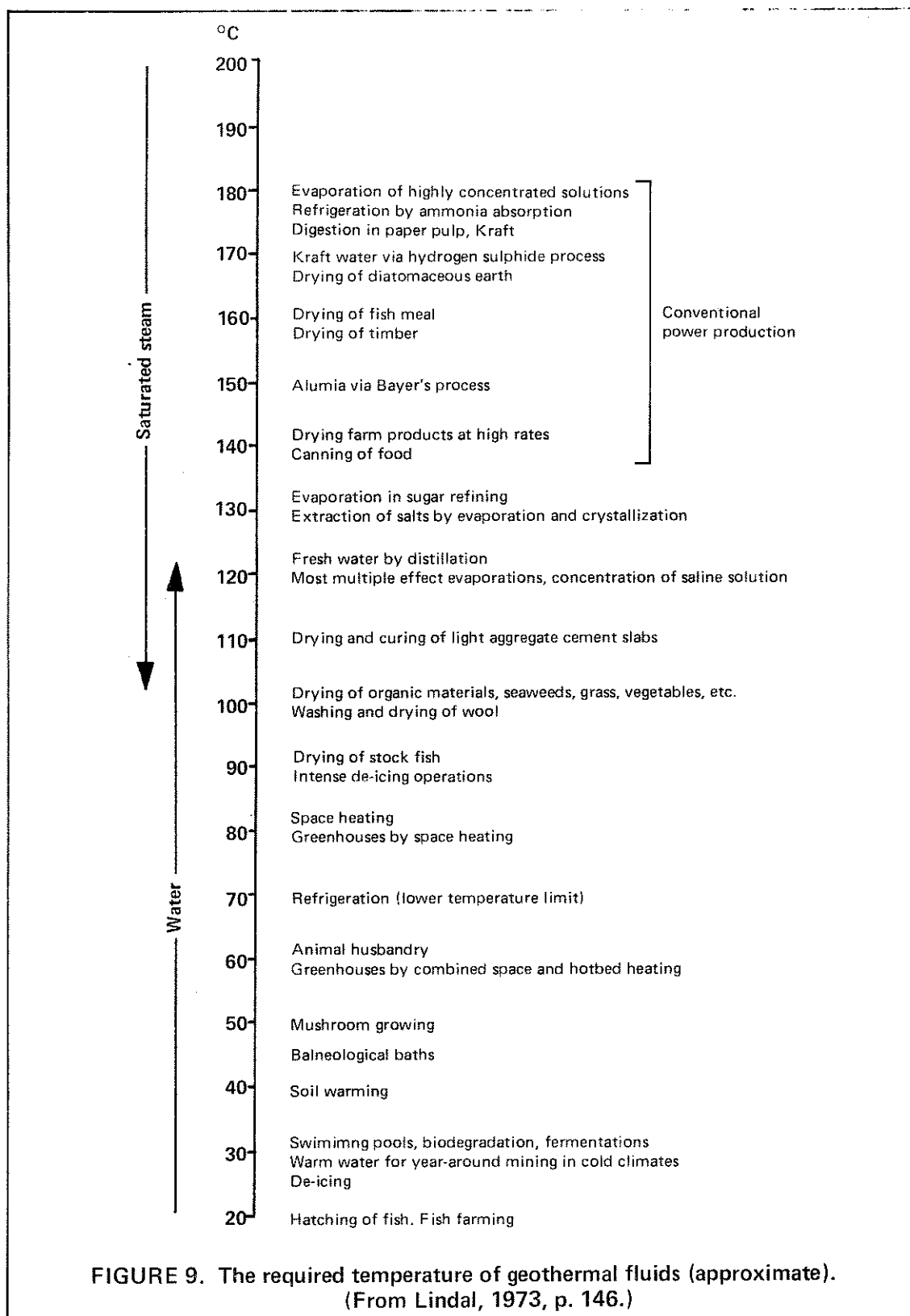
10. The depths postulated as necessary to give rise to the measured surface temperature are reasonable for the origin of these waters.

An exception to these general conclusions is the well at Magic Hot Springs (1S-17E-23aab1) near the north shore of Magic Reservoir (fig. 4). Water from this well contains 1,213 mg/l dissolved solids, 105 mg/l silica, and is higher in chloride (85 mg/l) than other thermal spring and well waters in the general area. This well was drilled in 1965 above the site of a warm spring which subsequently ceased to flow. Surface temperature of the spring water before drilling of the well was 36°C (Ross 1971, p. 56). When measured in the fall of 1973 the well had a surface temperature of 72°C. In 1975, during attempts to cap this well, artesian pressures reached 30 psig (pounds per sq. in. gauge), then started dropping. The owners were in fear of losing the well and removed the newly installed valve. These efforts increased surface temperature by 2°C to 74°C and discharged to approximately 250 liters per min.

The indicated disequilibrium conditions (Na-K-Ca geochemical thermometer differs from measured surface temperatures by more than 20°C, Appendix p. 39) could mean a possibility of mixing of the thermal with nonthermal ground waters. The proximity of the well to Magic Reservoir leads one to suspect that cold water leakage from Magic Reservoir could be entering the thermal water conduit system that supplies Magic Hot Springs well. Mixing model calculations indicate that the hot water component of this mixed (?) water may have reached temperatures as high as 200°C with cold water making up about 70% of total water (Appendix, fig. 3). Even if mixing is not taking place the 150-175°C temperatures predicted by the other geochemical thermometers are close to that temperature now considered necessary for a binary cycle geothermal power plant. The high chloride content (greater than 50 mg/l) would indicate that this system would probably be a hot water rather than a dry steam system.

The marked difference in chemistry between Magic Hot Springs well waters and other thermal waters in the Camas Prairie area would indicate: (1) Magic Hot Spring well waters have been at higher temperatures than the other thermal waters in the area, and/or (2) the aquifer or reservoir rocks for Magic Hot Springs well waters is mineralogically and/or chemically different from the aquifer or reservoir rock for the rest of the Prairie area. Although in many instances it is possible, using geochemical methods, to determine the aquifer or rock type from which thermal waters are in equilibrium, available data does not indicate which rock type could constitute an aquifer. The geology of the area would, however, suggest the aquifer to be either Quaternary alluvium, Middle Pliocene basalts of the Idaho Group, Lower Pliocene Idavada volcanic rocks, Eocene to Miocene Challis volcanic rocks, Cretaceous granitic rocks, or perhaps a combination of two or more of these.

The heat source for these waters could be either (1) an intruded sill or stock, related perhaps to the Holocene basalt flows found south of Magic Reservoir, or (2) a regionally high geothermal gradient and heat flow. Brott and others (1976) have determined that geothermal gradients and heat flow along the margins of the Snake River Plain are higher (about 3 HFU) than the regional norm which would indicate a regional heat source rather than a localized anomaly.



CONCLUSIONS

With the exception of Magic Hot Springs well water, the Camas Prairie thermal waters are probably meteoric waters circulating to shallow (approximately 1,200 m) depths along fractures or fissures within the granitic rocks underlying and along the margins of the Prairie. Heated waters are discharging upward into the sediments of the Prairie, perhaps through faults or fissures within the underlying granite concealed by valley fill. Some water subsequently discharges to the surface, forming springs. The source of the heat related to the granitic rocks is unknown.

The possibility of a large thermal aquifer or reservoir within the sediments filling the basin is negligible due to the apparent shallow depth of the valley fill materials as shown by the two wells penetrating the entire thickness of sediments near the basin center. Any possibility of a large thermal reservoir could lie in large faults in highly fractured granitic rock underlying the Prairie. Fracture permeability may allow sufficient circulation and recharge to allow large volumes of water to be withdrawn if the fault system could be penetrated by drilling. Hot and cold ground waters at depth probably are not mixing to any apparent degree. The thermal waters ascending from shallow depths could be cooling by conduction during their ascent to the surface.

Maximum temperatures encountered in drilling to 900 to 1,500 m are probably only about 100°C. Temperatures of this magnitude would be sufficient to have some industrial applications. These industrial applications and approximate temperatures necessary for them are shown in figure 9. Near Magic Hot Springs temperatures between 150° and 200°C might be found by deep drilling, provided that quartz is the mineral phase controlling silica content in these thermal waters. These waters may be circulating to depths approaching 1,800-2,500 m along faults; or may be leakage from a reservoir heated by an above normal geothermal gradient from a regionally high heat flow, or, from a shallow localized heat source related perhaps to the Holocene basalt flows found south of Magic Reservoir.

RECOMMENDATIONS

The thermal water geochemistry and drilling history, as well as the Holocene basalt flows near Magic Hot Springs well, show definite promise of hotter water with deeper drilling.

Before any deep exploration drilling activity, however, studies should determine the structural control of the thermal water source, and the depth and lateral limits of this source. With these as objectives, several methods of further study are suggested.

Reconnaissance surface geologic, high and low altitude air photo, and satellite imagery mapping should reveal faulting, fissuring and fracture patterns defined in the granites and volcanics surrounding Camas Prairie and Magic Reservoir, and in certain instances, could be used to obtain information on basement rock structures. This could shed some light on the structural control of Magic Hot Spring thermal waters.

Monitored seismic ground noise might help define ground movement, thereby giving more information on subsurface fault and fracture patterns.

Several heat flow holes drilled in the reservoir area should be constructed to measure the local heat flow.

Several resistivity profile lines run near the reservoir could establish the presence, size, shape, and depth of low resistivity zones indicative of thermal reservoir or aquifers.

These geophysical methods, if proved positive, would indicate a site for deep exploration drilling.

Activities related to exploration, large-scale withdrawal, and use of thermal waters in the Camas Prairie area should be carefully monitored. Cooperation between water users and state and local officials is necessary to avoid potential thermal and fluoride pollution, which could be a danger due to the higher temperatures and fluoride concentration in these waters should large-scale withdrawal be attempted.

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GEOCHEMICAL THERMOMETERS

Young and Mitchell (1973) gave a brief review of the then available geochemical thermometers. Their summary is as follows:

"Summary of Geochemical Thermometers Available

In recent years the concentrations of certain chemical constituents dissolved in thermal waters have been used to estimate water temperatures in the thermal aquifer. However, these geochemical thermometers are useful only if the geothermal system is of the more common hot-water type rather than of the vapor-dominated or steam type, none of which is known to occur in Idaho.

Geochemical thermometers that are useful in describing and evaluating geothermal systems (excluding the sodium-potassium-calcium thermometer) have been summarized by White (1970). Part of his summary is as follows:

'Chemical indicators of subsurface temperatures in hot-water systems.

Indicator	Comments
1) SiO_2 content	Best of indicators; assumes quartz equilibrium at high temperature, with no dilution or precipitation after cooling.
2) Na/K	Generally significant for ratios between 20/1 to 8/1 and for some systems outside these limits; see text.
3) Ca and HCO_3 contents	Qualitatively useful for near-neutral waters; solubility of CaCO_3 inversely related to subsurface temperatures; see text and ELLIS (1970).
4) Mg; Mg/Ca	Low values indicate high subsurface temperature, and vice versa.
5) ***	***
6) Na/Ca	High ratios may indicate high temperatures (MAHON, 1970) but not for high-Ca brines; less direct than 3?
7) $\text{Cl}/\text{HCO}_3 + \text{CO}_3$	Highest ratios in related waters indicate highest subsurface temperatures (FOURNIER, TRUESDELL 1970) and vice versa.
8) Cl/F	High ratios may indicate high temperature (MAHON, 1970) but Ca content (as controlled by pH and CO_3^{2-} contents) prevents quantitative application.

9) ***

10) Sinter deposits

Reliable indicator of subsurface temperatures (now or formerly) 180°C.

11) Travertine deposits

Strong indicator of low subsurface temperatures unless bicarbonate waters have contacted limestone after cooling.'

The general principles and assumptions on which the use of geochemical thermometers (White, 1970) is based are: (1) the chemical reactions controlling the amount of a chemical constituent taken into solution by hot water are temperature dependent; (2) an adequate supply of these chemical constituents is present in the aquifer; (3) chemical equilibrium has been established between the hot water and the specific aquifer minerals which supply the chemical constituents; (4) hot water from the aquifer flows rapidly to the surface; and (5) the chemical composition of the hot water does not change as it ascends from the aquifer to the surface.

The fact that these principles and assumptions more often than not cannot readily be verified in a field situation requires that the concept of geochemical thermometers be applied with caution and in full recognition of the uncertainties involved. With that understanding, geochemical thermometers provide a useful point of departure for reconnaissance screening and provisional evaluation of thermal areas.

Silica Geochemical Thermometer

The silica method of estimating aquifer temperatures (Fournier and Rowe, 1966) appears to be the most accurate and useful proposed to date. Experimental evidence has established that the solubility of silica in water is most commonly a function of temperature and the silica species being dissolved, (fig. 1).

Practical use of the silica geochemical thermometer assumes that there is

equilibration of dissolved silica with quartz minerals in high-temperature aquifers and that the equilibrium composition is largely preserved in the silica-bearing thermal waters during their ascent to the surface. White (1970) stated that while equilibrium is generally attained at high aquifer temperatures, silica may precipitate rapidly as waters cool to about 180°C and, therefore, the silica method commonly fails to predict actual aquifer temperatures much above 180°C. The rate of precipitation of silica decreases rapidly as the temperature cools below 180°C.

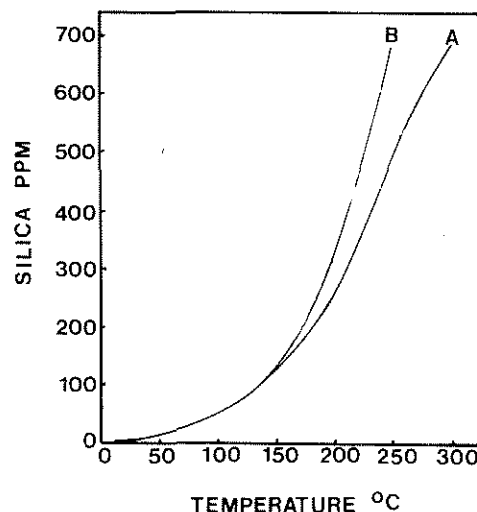


Figure 1. Silica concentration in geothermal water vs. estimated temperature of last equilibration. Curve A applies to waters cooled entirely by heat conduction. Curve B applies to waters cooled entirely by adiabatic expansion at constant enthalpy. (From Fournier and Rowe, 1966.)

White (1970) also cautioned against using the silica geochemical thermometer in acid waters which have a low chloride concentration, because at temperatures near or below 100°C these waters are actively decomposing silicate minerals and thereby releasing highly soluble amorphous SiO₂. In this case, the basic assumption of equilibration with quartz would be rendered invalid."

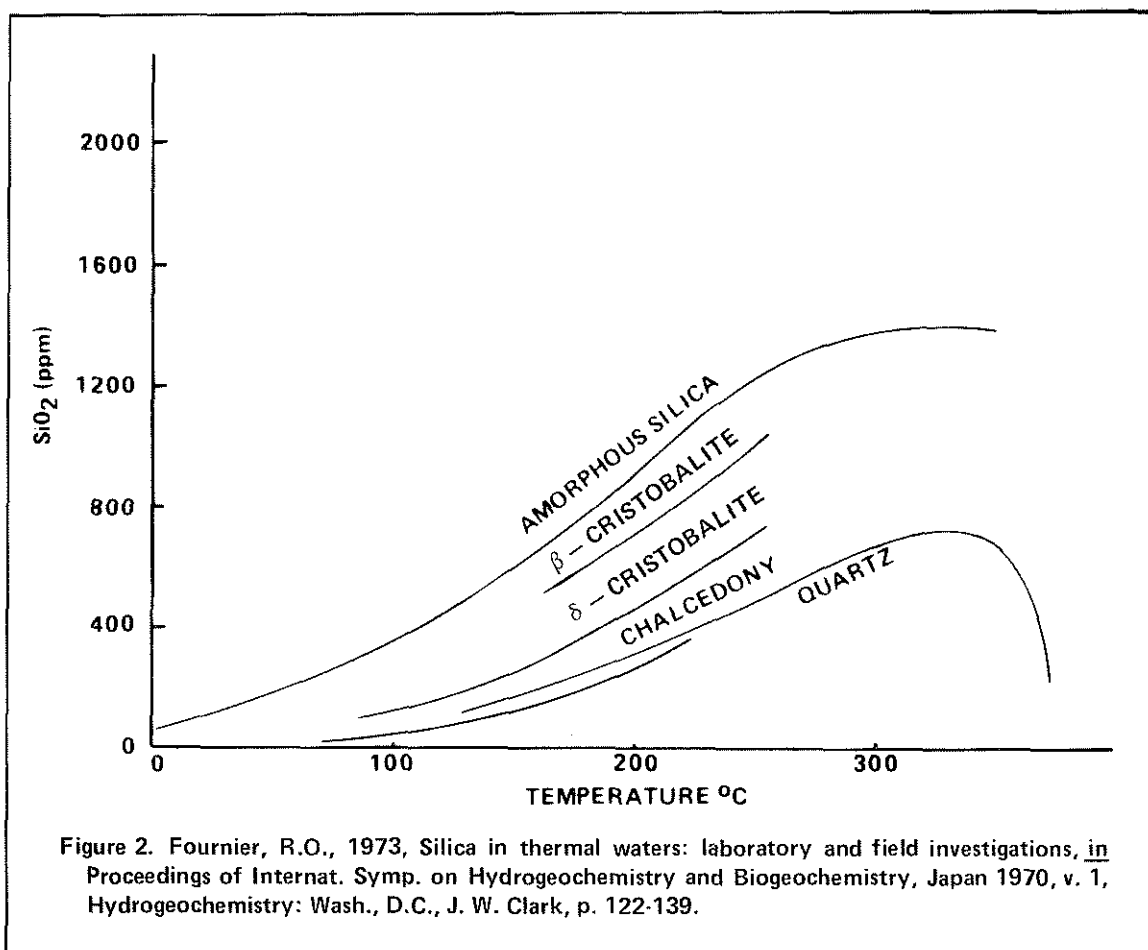
The amorphous silica curve (fig. 2) would give more accurate aquifer temperature predictions in acid waters.

Arnórsson (1970, p. 537, 1975, p. 763) found that chalcedony generally controls silica concentration in Iceland's thermal waters when aquifer temperatures are below 100-110°C. The chalcedony curve

(fig. 2) probably should be given consideration when the silica method using the quartz curve indicates temperatures about 10-20°C above Arnórsson's 110°C upper limit.

"The Sodium-Potassium and Sodium-Potassium-Calcium Geochemical Thermometers

The sodium-potassium (Na/K) geochemical thermometer plots the log of the atomic ratios of Na/K against the reciprocal of the absolute temperature. White (1970) stated that ratios are of general significance only in the ratio range between 8/1 and 20/1. He also reported that Na/K temperatures are not significant for most



acid waters, although a few acid-sulfate chloride waters yield reasonable temperatures. Fournier and Truesdell (1973) point out that Ca enters into silicate reactions in competition with Na and K and the amount of Ca in solution is greatly dependent upon carbonate equilibria. Calcium concentration from carbonates decreases as temperature increases, and may increase or decrease as the partial pressure of carbon dioxide increases, depending on pH considerations. Therefore, the Na/K ratio should not be used for purposes of geochemical thermometry when partial pressures of carbon dioxide are large, as higher carbon dioxide partial pressures may permit more Ca to remain in solution and consequently a smaller Na/K ratio. Fournier and Truesdell (1973) suggest that this ratio should not be used when the $\sqrt{M_{Ca}/M_{Na}}$ (square root of molar concentration of calcium/molar concentration of sodium) is greater than 1.

The sodium-potassium-calcium (Na-K-Ca) geochemical thermometer devised by Fournier and Truesdell (1973) is a method of estimating aquifer temperatures based on the molar concentrations of Na, K, and Ca in natural

thermal waters. Accumulated evidence suggests that thermal, calcium-rich waters do not give reasonable temperature estimates using Na/K atomic ratios alone, and that the Ca concentration must be given consideration.

Fournier and Truesdell (1973) showed that molar concentrations of Na-K-Ca for most geothermal waters cluster near a straight line when plotted as the function $\log K^* = \log (Na/K) + \beta \log (\sqrt{Ca}/Na)$ versus the reciprocal of the absolute temperature, where β is either 1/3 or 4/3, depending upon whether the waters equilibrated above or below about 100°C and where K^* is an equilibrium constant. For most waters they tested, the Na-K-Ca method gave better results than the Na/K method. It is generally believed that the Na-K-Ca geochemical thermometer will give better results for calcium-rich environments provided calcium carbonate has not been deposited after the water has left the aquifer. Where calcium carbonate has been deposited, the Na-K-Ca geochemical thermometer may give anomalously high aquifer temperatures. Fournier and Truesdell (1973) caution against using the Na-K-Ca geochemical thermometer in acid waters that are low in chloride."

Dilution Effects, the Use of the Geochemical Thermometers and Mixing Models

Dilution effects caused by mixing of thermal with nonthermal waters can be a cause of erroneous temperature estimates. Cool groundwaters containing low silica concentrations that mix with thermal waters rich in silica would effectively lower the silica concentration of the thermal water, and a lower aquifer temperature would be indicated. Generally, the possible effect of both dilution and enrichment of thermal waters on the temperature calculated using any geochemical thermometer must be considered.

Fournier and others (1974) suggested several starting assumptions to apply to the interpretation of chemical data for hot springs and wells where little information on hydrologic conditions is available. They emphasized that these assumptions are not hard, fast rules applicable to every situation. Their recommended procedures are based on: (1) the discharge of the spring or well, and (2) the recorded surface temperature, as outlined below.

	Small Discharge	Large Discharge
Boiling Springs	Assume mostly conductive cooling. Apply chemical indicators assuming little or no steam loss (adiabatic cooling).	Assume steam loss (adiabatic cooling). Assume maximum steam loss, apply geochemical thermometers accordingly.
Springs below boiling	Probably no clearcut interpretation. May be (1) water that has never been very hot, (2) mixed water from different sources at different temperatures, (3) hot water cooled by conduction. Indicated temperatures most likely, minimum.	Assume no conductive cooling. Geochemical thermometers, particularly Na-K-Ca, if within + 25°C of measured surface temperature may be suggestive of equilibrium conditions. Higher indicated temperatures suggests a mixed water.

Small discharge was defined to be less than 200 l/min for single isolated spring, and 20 l/min for single spring vents of larger groups.

Fournier and Truesdell (1974) have developed a method of testing thermal waters to determine if mixing may be taking place. They maintain that mixing should be suspect where: (1) regular variations in surface temperatures with chloride, boron, or other nonreactive chemical constituents from several springs of an area are observed, (2) the Na-K-Ca geochemical thermometer indicates nonequilibrium conditions (Na-K-Ca indicated temperatures varies from the observed surface temperature by more than 20°C).

Under ideal conditions, Fournier and Truesdell's mixing models allow prediction of the temperature of the hot water before mixing. The models assume that enthalpy (heat content - H_c) of the cold water multiplied by the fraction of cold water (X) plus the enthalpy of the hot water (H_h) multiplied by the fraction of the hot water (1-X) is equal to the enthalpy of the emerging spring water (H_{spg}). Stated mathematically:

$$(H_c)(X) + (H_h)(1-X) = H_{spg} \quad (1)$$

Similarly,

$$(Si)(X) + (Si_h)(1-X) = Si_{spg} \quad (2)$$

Where Si_c is the silica content of cold spring, Si_{spg} is the silica content of the hot spring water and Si_h is the enthalpy value for silica in hot water (table 1 - equation 5). Equations 1 and 2 are each solved for the unknown X by simple algebraic rearrangement to give equations 3 and 4.

Fournier and Truesdell's suggested graphical method of solution for mixing model 1, in which the enthalpy of the hot water plus separated steam which heats cold water is the same as the initial enthalpy of hot water before steam separates (no steam loss by system; hence, no evaporative concentration), is as follows:

- "1. Assume a series of values of temperature of hot water and using this corresponding enthalpy values listed in table 1 calculate X_t for each one, using equation 3.

$$X_t = \frac{(\text{Enthalpy of hot water}) - (\text{temp of warm spg})}{(\text{Enthalpy of hot water}) - (\text{temp of cold spg})} \quad (3)$$

2. Plot the calculated values of X_t vs. the assumed temperatures from which the hot water enthalpy values were derived. (See fig. 3, curve A for sample plot.)
3. Using a series of silica contents of hot water appropriate for the temperatures listed in table 1 evaluate X_{Si} for each silica content using equation 4.

$$X_{Si} = \frac{(\text{Silica in hot water}) - (\text{Silica in warm spg})}{(\text{Silica in hot water}) - (\text{Silica in cold spg})} \quad (4)$$

4. On the same graph previously used, plot the calculated values of X_{Si} vs. the temperatures for which the silica contents were obtained (see fig. 3, curve B)."

Table 1¹

Enthalpies of liquid water and quartz solubilities at selected temperatures and at pressures appropriate for steam and liquid water to coexist. Enthalpies from Keenan et al. (1969). Quartz solubilities at and below 225°C from Morey et al. (1962); above 225°C from unpublished data of R. O. Fournier.

Temperature °C	Enthalpy cal/gm	Silica ppm
50	50.0	13.5
75	75.0	26.6
100	100.1	48
125	125.4	80
150	151.0	125
175	177.0	185
200	203.6	265
225	230.9	365
250	259.2	486
275	289.0	614
300	321	692

¹Table from Fournier and Truesdell, 1974.

Table 2 gives the calculated X_t and X_{Si} values at selected temperatures and silica concentrations for this mixing model from sampled springs and wells in the northern Cache Valley area.

The intersection of the two curves represent the percent of cold water mixing with the hot (read directly below intersection point on the horizontal axis of the graph) and the temperature of the hot water component before mixing (read on the vertical axis of the graph directly to the left of the intersection point).

Their solution for mixing model 2, in which the enthalpy of hot water in the zone of mixing is less than the enthalpy of the hot water at depth, due to escape of steam during ascent is as follows:

- "1. Use the atmospheric boiling temperature for the value of H_h in equation 2 and calculate the corresponding value of X .
2. Use that value of X in equation 3 to estimate the residual silica content of hot water at t_s .
3. Use the calculated residual silica content and curve A of Fournier and Rowe (1966, fig. 5) to estimate the original subsurface temperature before separation of steam. Curve A of Fournier and Rowe is roughly approximated by the equation

$$-\log C = \frac{1522}{t_{oC} - 273} - 5.75 \quad (5)$$

where C is the silica concentration, and t is temperature in degrees Celsius."

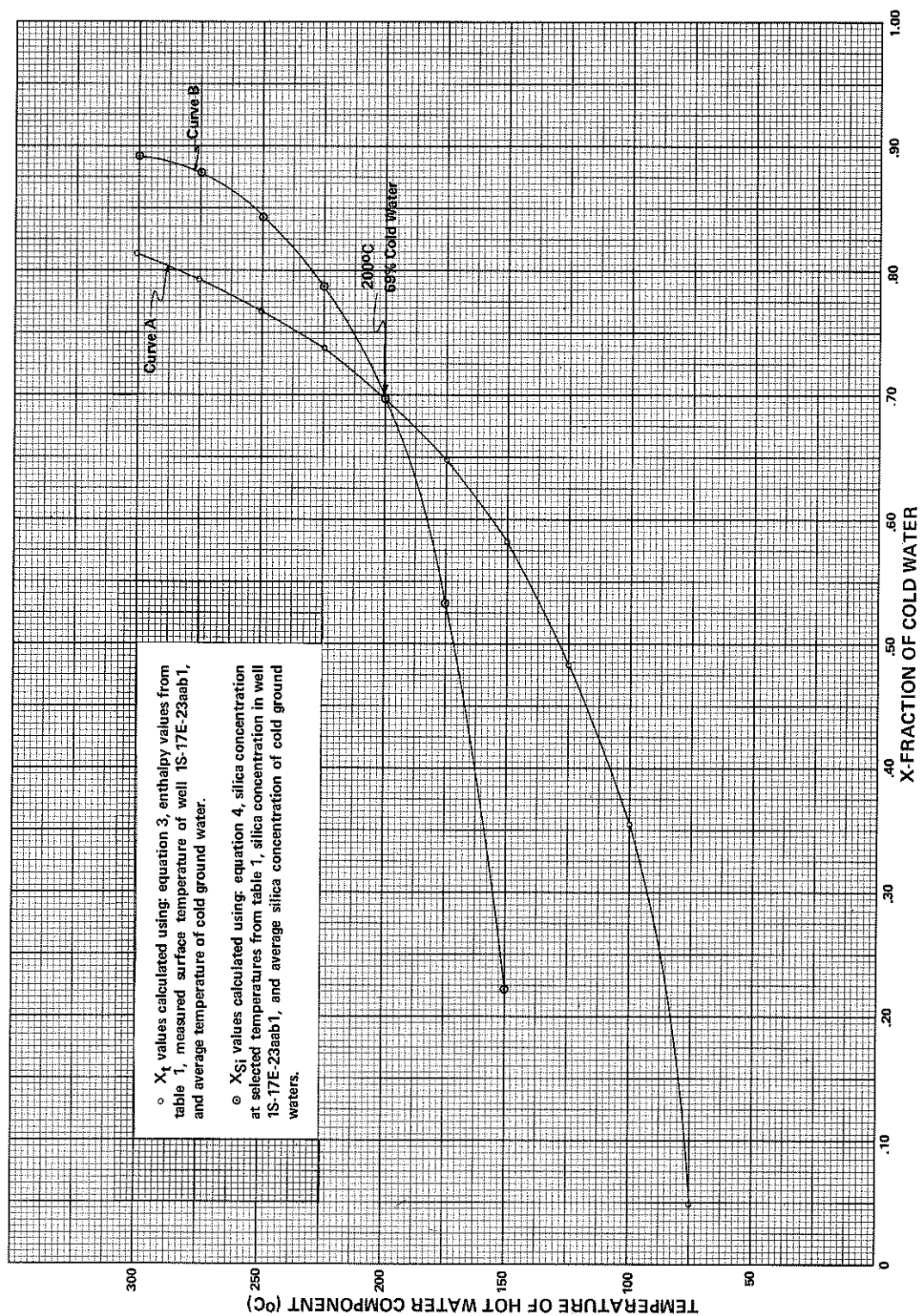


FIGURE 3. Fraction of cold water relative to temperature for well 1S-17E-23aab1.

TABLE 2
X_t AND X_{Si} VALUES AT SPECIFIED TEMPERATURES AND SILICA CONCENTRATIONS
FOR THERMAL WATERS OF THE CAMAS PRAIRIE AREA
(Temperature °C)

Spring No. 1N-13E-32abc1S Surface temperature = 60° Silica = 81 mg/l Background silica = 35 mg/l Background temperature = 15° Boiling temperature = 95°				Spring No. 1N-13E-32abc3S Surface temperature = 64° Silica = 78 mg/l Background silica = 35 mg/l Background temperature = 15° Boiling temperature = 95°				Spring No. 1N-15E-14ada2S Surface temperature = 55° Silica = 83 mg/l Background silica = 35 mg/l Background temperature = 15° Boiling temperature = 95°			
T	X _t	X _{Si}		T	X _t	X _{Si}		T	X _t	X _{Si}	
75	0.250	-		75	0.183	-		75	0.333	-	
100	.471	-		100	.424	-		100	.530	-	
125	.592	0.042		125	.556	0.104		125	.638	-	
150	.669	.489		150	.640	.522		150	.706	0.467	
175	.722	.693		175	.698	.713		175	.753	.680	
200	.761	.800		200	.740	.813		200	.788	.791	
225	.792	.861		225	.773	.870		225	.815	.855	
250	.816	.897		250	.799	.904		250	.836	.892	
275	.836	.921		275	.821	.926		275	.854	.917	
300	.853	.930		300	.840	.935		300	.869	.927	
Temperature of unmixed hot water = 185°. Percent of cold water = 73.				Temperature of unmixed hot water = 172°. Percent of cold water = 60.				Temperature of unmixed hot water = 198°. Percent of cold water = 78.			
Spring No. 1N-13E-32abc2S Surface temperature = 67° Silica = 78 mg/l Background silica = 35 mg/l Background temperature = 15° Boiling temperature = 95°				Spring No. 1N-15E-14ada1S Surface temperature = 55° Silica = 82 mg/l Background silica = 35 mg/l Background temperature = 15° Boiling temperature = 95°				Spring No. 1N-15E-14ada3S Surface temperature = 45° Silica = 78 mg/l Background silica = 35 mg/l Background temperature = 15° Boiling temperature = 95°			
T	X _t	X _{Si}		T	X _t	X _{Si}		T	X _t	X _{Si}	
75	0.133	-		75	0.333	-		75	0.500	-	
100	.389	-		100	.530	-		100	.647	-	
125	.529	0.104		125	.638	0.021		125	.728	0.104	
150	.618	.522		150	.706	.478		150	.779	.522	
175	.679	.713		175	.753	.687		175	.815	.713	
200	.724	.813		200	.788	.796		200	.841	.813	
225	.759	.870		225	.815	.858		225	.861	.870	
250	.787	.904		250	.836	.895		250	.877	.904	
275	.810	.926		275	.854	.919		275	.891	.926	
300	.830	.935		300	.869	.928		300	.902	.935	
Temperature of unmixed hot water = 168°. Percent of cold water = 66.				Temperature unmixed hot water = 197°. Percent of cold water = 78.				Temperature of unmixed hot water = 219°. Percent of cold water = 85.			

Spring No. 1S-12E-16caba1S

Surface temperature = 45°
Silica = 68 mg/l
Background silica = 35 mg/l
Background temperature = 15°
Boiling temperature = 95°

T	X _t	X _{Si}
75	0.500	-
100	.647	-
125	.728	0.313
150	.779	.633
175	.815	.780
200	.841	.857
225	.861	.900
250	.877	.926
275	.891	.943
300	.902	.950

Temperature of unmixed hot water = 192°.
Percent of cold water = 83.

Spring No. 1S-12E-16cab1S

Surface temperature = 49°
Silica = 68 mg/l
Background silica = 35 mg/l
Background temperature = 15°
Boiling temperature = 95°

T	X _t	X _{Si}
75	0.433	-
100	.600	-
125	.692	0.313
150	.750	.633
175	.790	.780
200	.820	.857
225	.843	.900
250	.861	.926
275	.876	.943
300	.889	.950

Temperature of unmixed hot water = 180°.
Percent of cold water = 79.

Well No. 1S-13E-22ccc1

Surface temperature = 26°
Silica = 78 mg/l
Background silica = 35 mg/l
Background temperature = 15°
Boiling temperature = 95°

T	X _t	X _{Si}
75	0.817	-
100	.871	-
125	.900	0.104
150	.919	.522
175	.932	.713
200	.942	.813
225	.949	.870
250	.955	.904
275	.960	.926
300	.964	.935

Hot water temperature calculation not possible.

Well No. 1S-13E-27ccb1

Surface temperature = 35°
Silica = 83 mg/l
Background silica = 35 mg/l
Background temperature = 15°
Boiling temperature = 95°

T	X _t	X _{Si}
75	0.667	-
100	.765	-
125	.819	-
150	.853	0.467
175	.877	.680
200	.894	.791
225	.907	.855
250	.918	.892
275	.927	.917
300	.935	.927

Hot water temperature calculation not possible.

Well No. 1S-13E-27ccb2

Surface temperature = 45°
Silica = 64 mg/l
Background silica = 35 mg/l
Background temperature = 15°
Boiling temperature = 95°

T	X _t	X _{Si}
75	0.500	-
100	.647	-
125	.728	0.396
150	.779	.678
175	.815	.807
200	.841	.874
225	.861	.912
250	.877	.935
275	.891	.950
300	.902	.956

Temperature of unmixed hot water = 179°.
Percent of cold water = 81.

Well No. 1S-13E-34bcc1

Surface temperature = 49°
Silica = 84 mg/l
Background silica = 35 mg/l
Background temperature = 15°
Boiling temperature = 95°

T	X _t	X _{Si}
75	0.433	-
100	.600	-
125	.692	-
150	.750	0.456
175	.790	.673
200	.820	.787
225	.843	.852
250	.861	.890
275	.876	.915
300	.889	.925

Temperature of unmixed hot water = 219°.
Percent of cold water = 83.

Table 2. X_t and X_{Si} Values at Specified Temperatures and Silica Concentrations for Thermal Waters of the Camas Prairie Area
(Temperature °C) (Continued)

Spring No. 1S-13E-34beb1S

Surface temperature = 73°
Silica = 84 mg/l
Background silica = 35 mg/l
Background temperature = 15°
Boiling temperature 95°

T	X_t	X_{Si}
75	0.033	-
100	.318	-
125	.475	-
150	.574	0.456
175	.642	.673
200	.692	.787
225	.731	.852
250	.762	.890
275	.788	.915
300	.810	.925

Temperature of unmixed hot water = 169°.
Percent of cold water = 62.

Well No. 1S-17E-23aab1

Surface temperature = 72°
Silica = 105 mg/l
Background silica = 35 mg/l
Background temperature = 15°
Boiling temperature = 95°

T	X_t	X_{Si}
75	0.050	-
100	.330	-
125	.484	-
150	.581	0.222
175	.648	.533
200	.698	.696
225	.736	.788
250	.767	.843
275	.792	.879
300	.814	.893

Temperature of unmixed hot water = 200°.
Percent of cold water = 69.

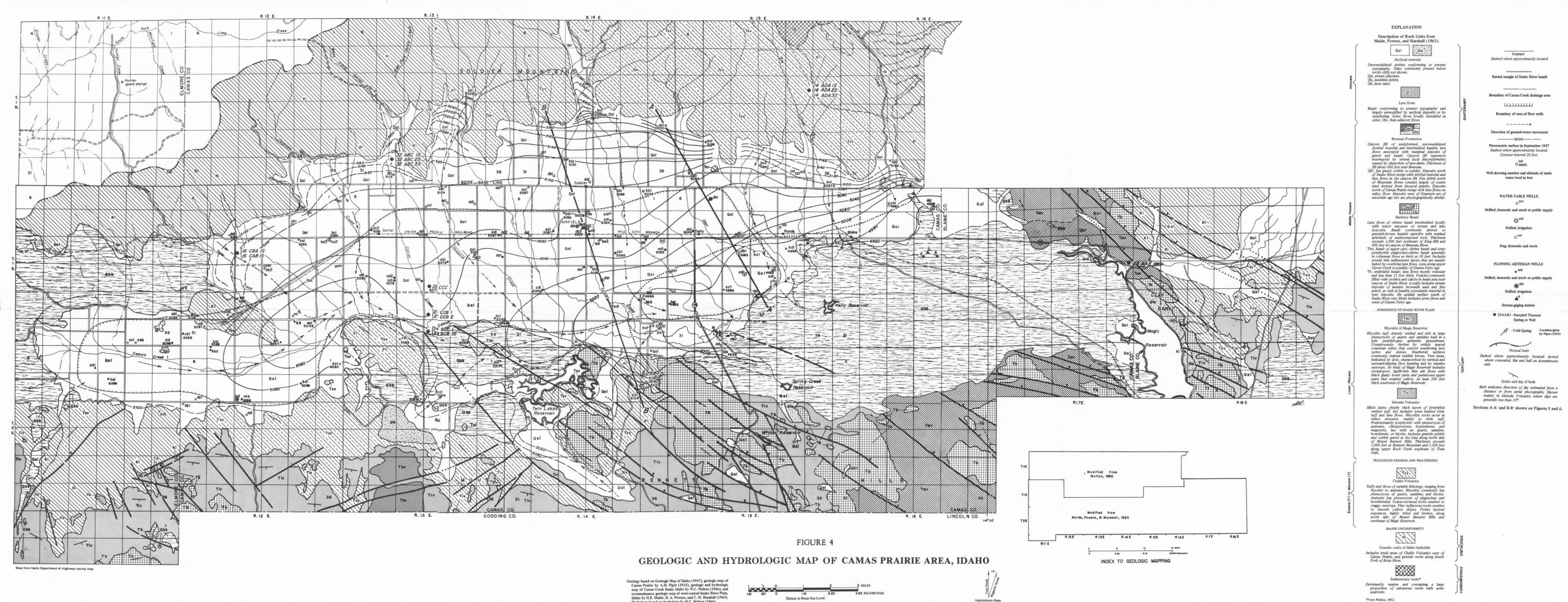
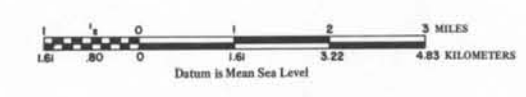


FIGURE 4
GEOLOGIC AND HYDROLOGIC MAP OF CAMAS PRAIRIE AREA, IDAHO

Geology based on Geologic Map of Idaho (1947), geologic map of Camas Prairie by A. M. Piper (1925), geologic and hydrologic map of Camas Creek Basin, Idaho by W. C. Walton (1966), and reconnaissance geologic map of west-central Snake River Plain, Idaho by H. E. Malde, H. A. Powers, and C. H. Marshall (1963). Hydrology based on hydrology by W. C. Walton (1966).



EXPLANATION

Description of Rock Units from Malde, Powers, and Marshall (1963).

Qal Surficial material
Unconsolidated detritus conforming to present topography. Tuff commonly present below rocky cliffs not shown.
Qal, stream alluvium.
Qal, landslide debris.
Qal, dune sand.

Q Lava flows
Basalt conforming to present topography and largely unmodified by surficial deposits or by weathering. Some flows locally identified as older, Q₁, than adjacent flows.

Br Brunson Formation
Canyon fill of unconsolidated, unconsolidated detrital material and interbedded basaltic lava flows associated with marginal deposits of gravel and basalt. Canyon fill sequences interrupted by several local disconformities caused by erosion of lava dams. Thickness of fill about 800 feet near Brunson. Deposits north of Snake River merge with detrital material and lava flows in the canyon fill. Fan debris north of Mountain Home consists largely of coarse sand derived from dissected granite. Deposits north of Camas Prairie merge with lava flows in valley floor. Deposits west of Granger are of uncertain age but are physiographically similar.

Ba Barbary Basalt
Lava flows of olivine basalt interbedded locally with minor amounts of stream and lake deposits. Basalt commonly altered to greenish-brown basaltic tuff with residual spherulites of unconsolidated rock. Thickness exceeds 1,000 feet northeast of King Hill and 800 feet in canyon of Brunson River. Tuff, basalt of upper part; olivine basalt and some porphyritic plagioclase-olivine basalt generally in columnar flows as thick as 50 feet. Includes several thin sedimentary layers that are usually baked by overlying lava flows. Lava along upper Clover Creek is possibly of Granger age.

Tv Tuffaceous basalt
Unconsolidated basaltic lava flows mostly vesicular and less than 15 feet thick. Vesicles commonly filled with zeolites and calcite in basin area near canyon of Snake River. Locally includes stream deposits of massive brownish sand and fine gravel, as well as basaltic pyroclastic material in vent deposits. On upland surface south of Snake River very likely includes some flows and vents of Granger age.

SUBSIDENCE OF SNAKE RIVER PLAIN

R Rhyolite of Magic Reservoir
Rhyolite tuff, densely welded and rich in large phenocrysts of quartz and sanidine held in a pale, porous, granular, aphanitic groundmass. Compactly broken by widely spaced columnar joints that control weathering into spires and domes. Weathered surfaces commonly stained reddish brown. Vent areas, indicated by dots, characterized by vertical and outward-dipping flow banding and by massive outcrops. At head of Magic Reservoir includes crystal-poor, lapilli-rich thin ash flows with black platy lower parts and punkstone upper parts that weather yellow. At least 500 feet thick southwest of Magic Reservoir.

M Mafic Volcanics
Silicic tuff; chiefly thick layers of destuffed welded tuff, but includes some bedded rhyolite tuff and lava flows. Rhyolite occurs in minor amounts, mainly as vitro, tuff. Predominantly porphyritic with phenocrysts of andesine, clinopyroxene, hypersthene, and magnetite, but with no quartz, sanidine, hornblende, or biotite. Includes granitic pebbles and cobbles gravel at the base along north side of Mount Bennett Hills. Thickness exceeds 2,000 feet at Bennett Mountain and 1,200 feet along upper Rock Creek southeast of Twin Falls.

PROLONGED EROSION AND WEATHERING

Ch Chalk Volcanics
Tuffs and flows of variable lithology, ranging from rhyolite to andesite. Rhyolite commonly has phenocrysts of quartz, sanidine, and biotite. Andesite has phenocrysts of plagioclase and hornblende. Coarse-textured rocks weather to craggy outcrops. Fine-textured rocks weather to smooth yellow slopes. Forms layered sequences, highly tilted and broken, along north side of Mount Bennett Hills and northeast of Magic Reservoir.

MAJOR UNCONFORMITY

K Granitic rocks of Idaho batholith
Includes small areas of Chalk Volcanics west of Camas Prairie, and gneissic rocks along South Fork of Boise River.

S Sedimentary rocks*
Dominantly marine and containing a large proportion of calcareous rocks with some quartzite.

*From Walton, 1962.

CONTACT
Dashed where approximately located

BURIED MARGIN OF SNAKE RIVER BASIN
.....

BOUNDARY OF CAMAS CREEK DRAINAGE AREA
.....

BOUNDARY OF AREA OF FLOW WELLS
.....

DIRECTION OF GROUND-WATER MOVEMENT
.....

PIEZOMETRIC SURFACE IN SEPTEMBER 1957
Dashed where approximately located.
Contour interval 20 feet.

WATER-TABLE WELLS
o
Drilled; domestic and stock or public supply
o
Drilled; irrigation
o
Dug; domestic and stock

FLOWING ARTESIAN WELLS
o
Drilled; domestic and stock or public supply
o
Drilled; irrigation
o
Stream-gaging station

23AAB1-Sampled Thermal Spring or Well
o
Cold Spring Location given by Figs. (1953)

Normal fault
Dashed where approximately located; dotted where concealed. Bar and ball on downthrown side.

Strike and dip of beds
Barb indicates direction of dip estimated from a distance or from aerial photographs. Dip mainly in Idaho Volcanics where dips are generally less than 10°.

Sections A-A' and B-B' shown on Figures 5 and 6.